

DAE δ ALUS

A Phased Neutrino Physics Program Using
Cyclotron Decay-at-Rest Neutrino Sources

TAUP 2013
Matt Toups, MIT

$(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ Oscillations at $2\pi E/L \sim |\Delta m_{13}^2|$

Are Sensitive to δ_{CP}

in a vacuum...

$$P = (\sin^2 \theta_{23} \sin^2 2\theta_{13}) (\sin^2 \Delta_{31}) \\ \mp \sin \delta (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}) (\sin^2 \Delta_{31} \sin \Delta_{21}) \\ + \cos \delta (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}) (\sin \Delta_{31} \cos \Delta_{31} \sin \Delta_{21}) \\ + (\cos^2 \theta_{23} \sin^2 2\theta_{12}) (\sin^2 \Delta_{21}).$$

We want to see
if δ is nonzero

terms depending on
mixing angles

terms depending on
mass splittings

$$\Delta_{ij} = \Delta m_{ij}^2 L / 4E_\nu$$

The Traditional Approach To $\bar{\nu}_e$ Appearance:

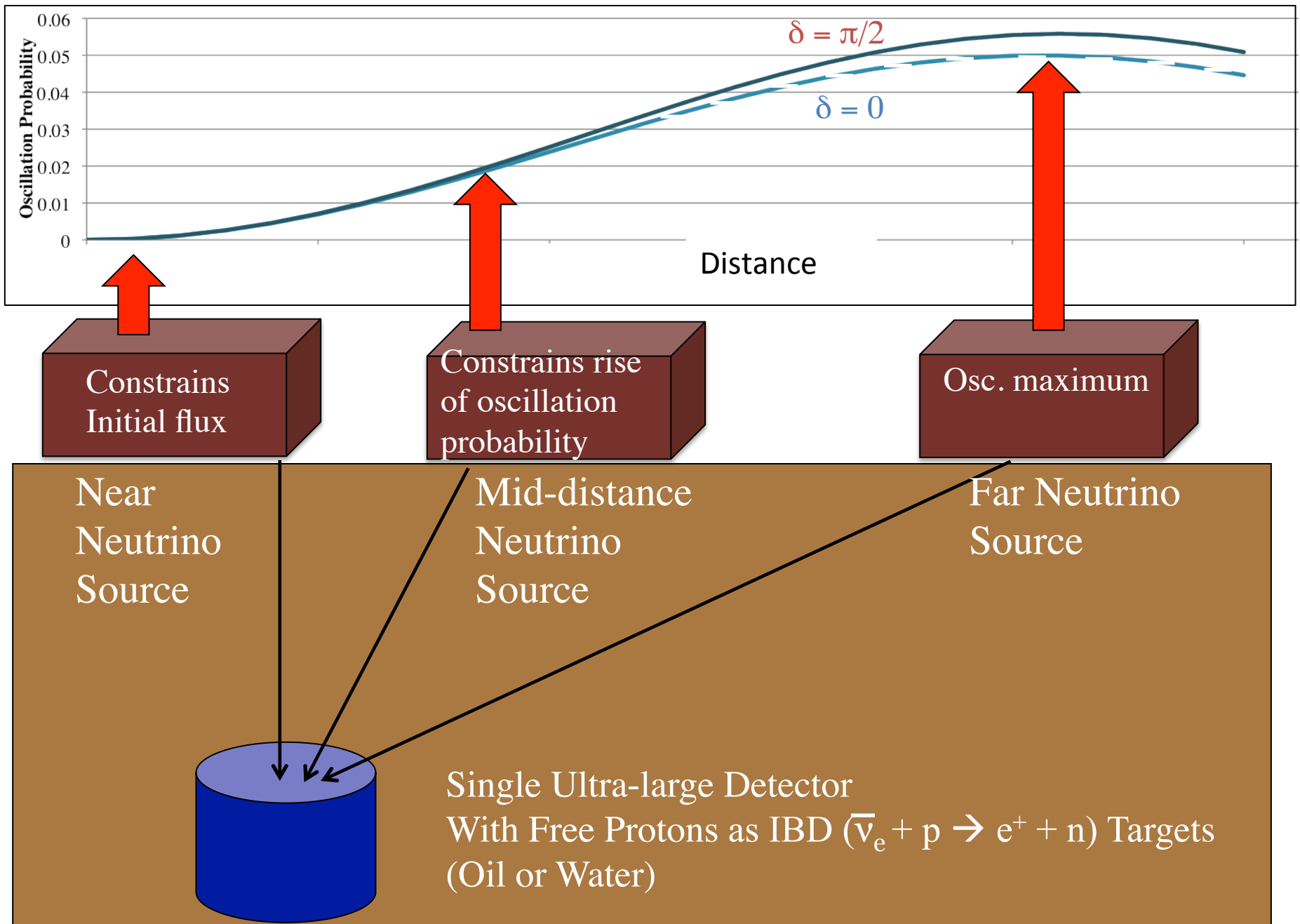
Single neutrino source

Multiple neutrino detectors at different baselines

The DAE δ ALUS Approach To $\bar{\nu}_e$ Appearance:

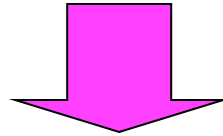
Multiple neutrino sources at different baselines

Single neutrino detector

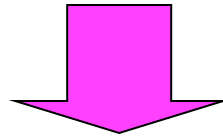


Measurement strategy:

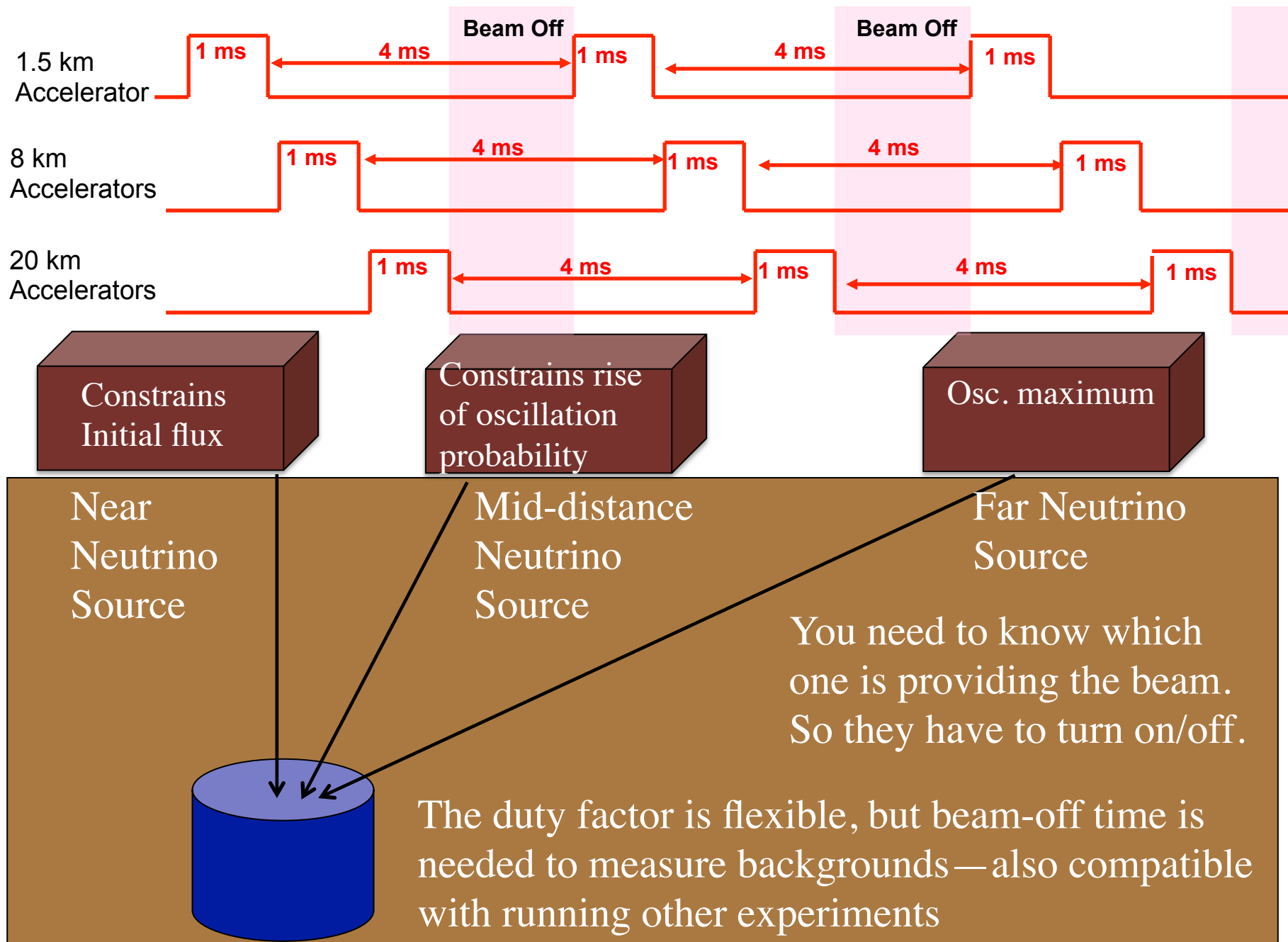
Using the **near** neutrino source
measure **absolute flux normalization** with ν_e -e events to $\sim 1\%$,
Also, measure the $(\nu_e O) \nu_e C$ event rate.



At far and mid-distance neutrino source,
Compare predicted to measured $\nu_e O$ ($\nu_e C$) event rates
to get the **relative flux normalizations between 3 sites**

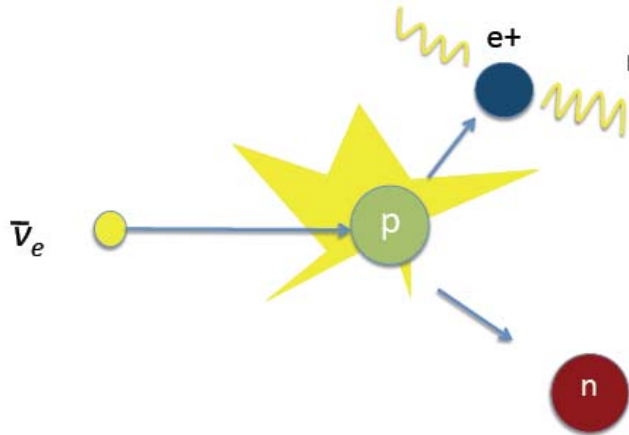


For all three neutrino sources,
given the known flux, **fit for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal**
with δ as a free parameter



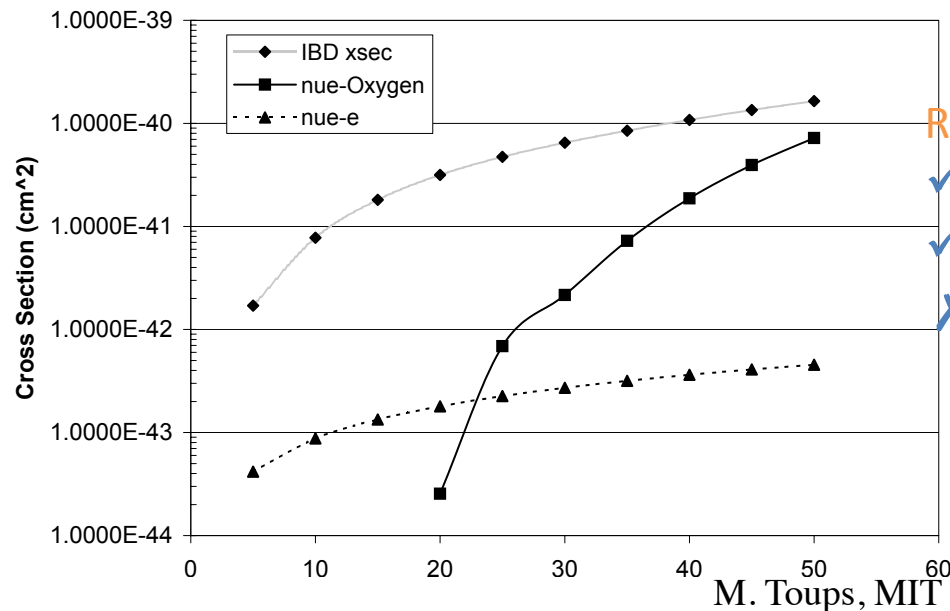
Detection Channel: Inverse β decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Ideal signal:

1. Delayed coincidence
2. Neutrino energy reconstructed
3. Large cross section
4. Cross section known to < 1%



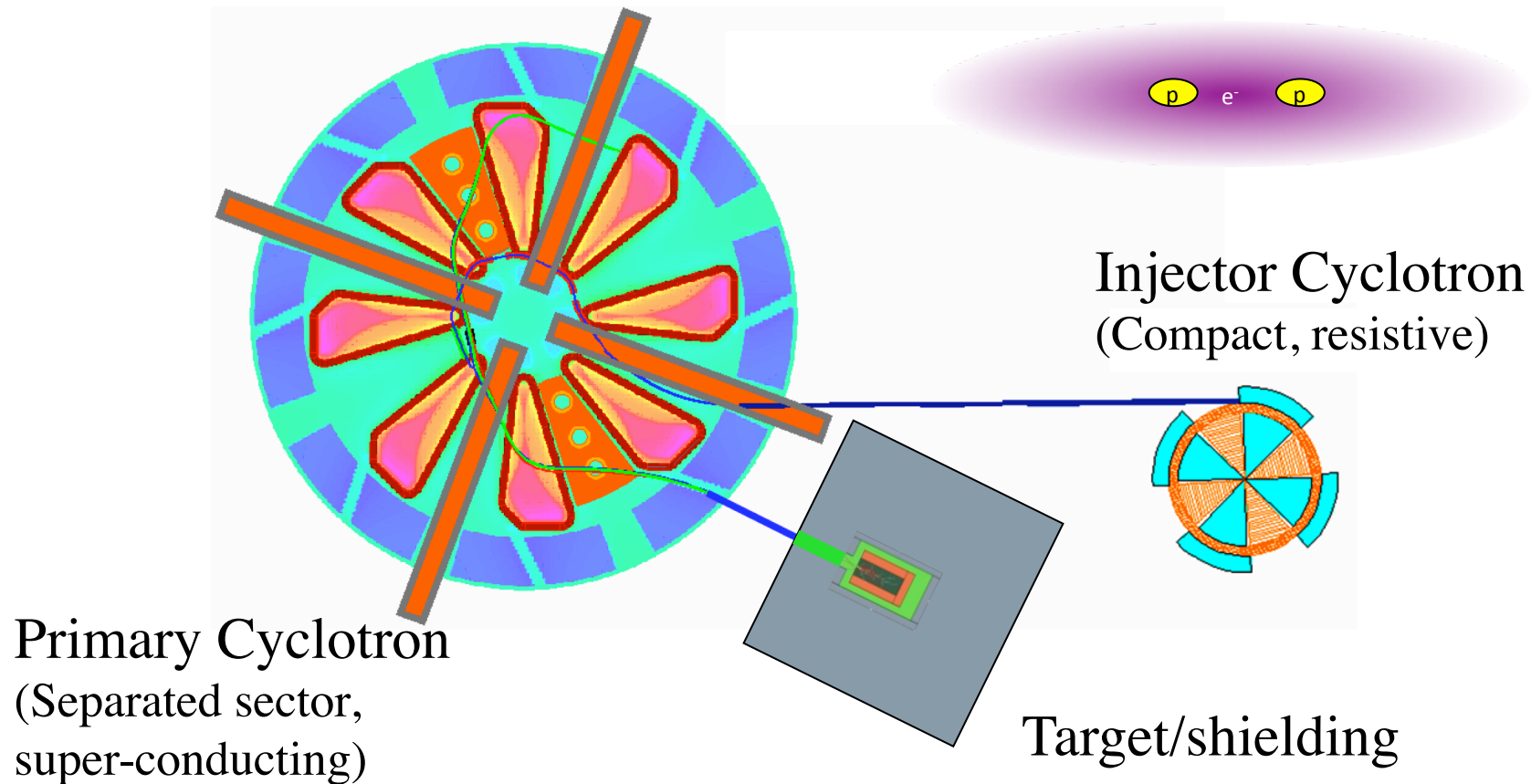
Requires free protons and n tagging!

✓ Gd-doped Water Cerenkov

✓ Scintillator detector

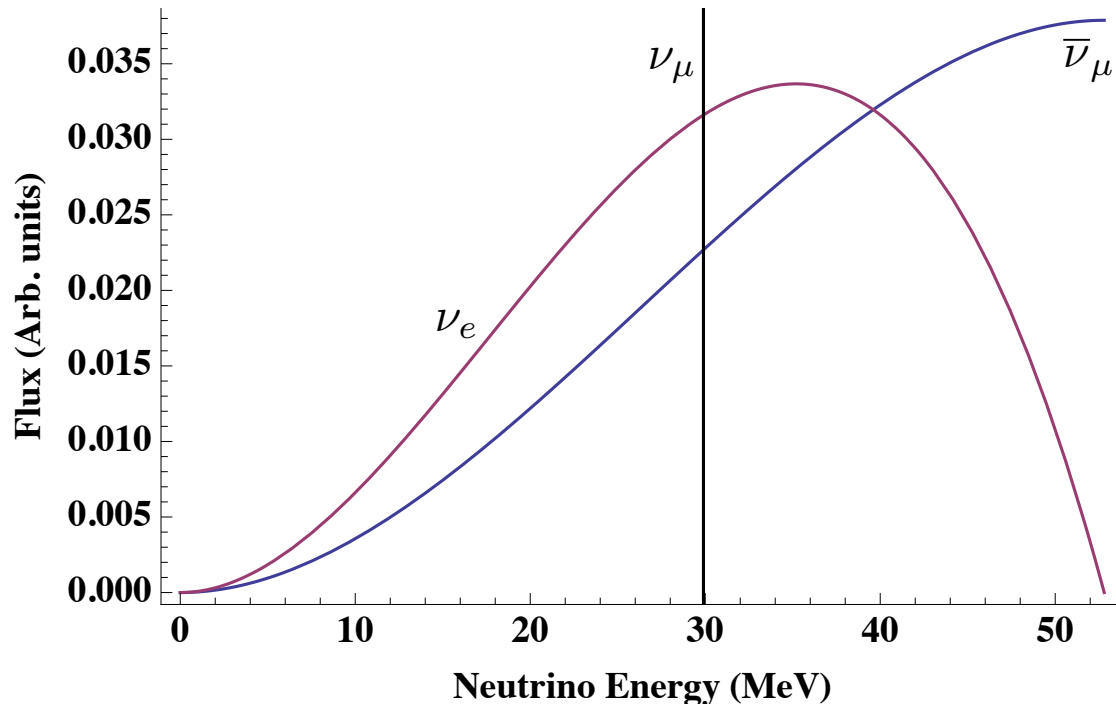
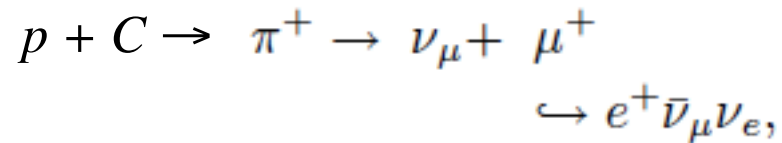
✗ Liquid Argon TPC

We use multiple “Accelerator Units” to produce our DAR beam,
Constructed out of Cyclotrons,
Which accelerate H_2^+ to 800 MeV/amu



The DAEδALUS Neutrino Source

π^+ decay-at-rest (DAR) beam:



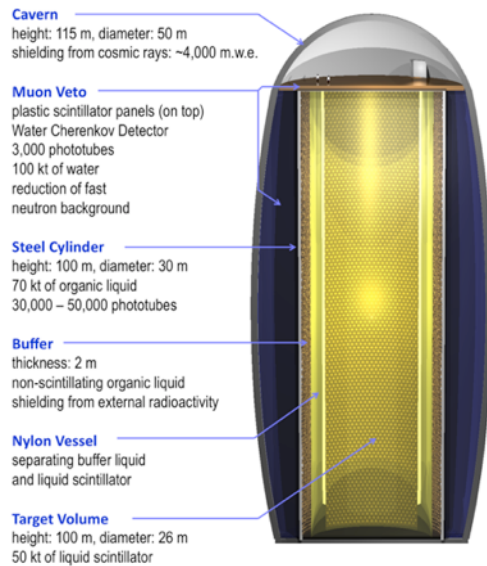
Shape driven by nature!

Only the normalization
varies from beam to beam

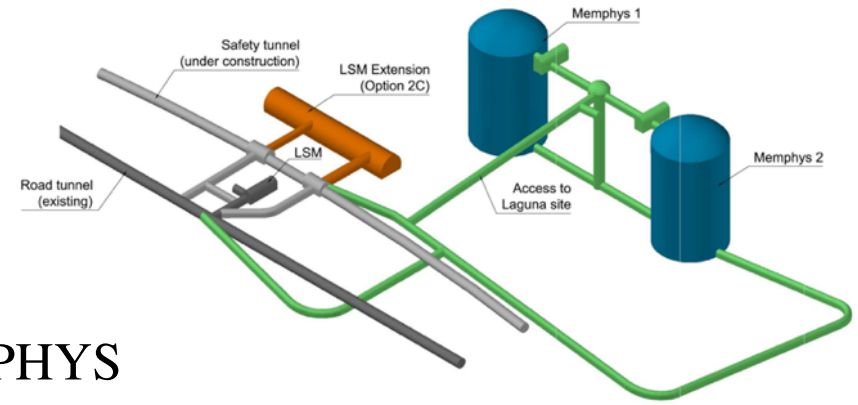
A great place to search for



Where can DAE δ ALUS run?



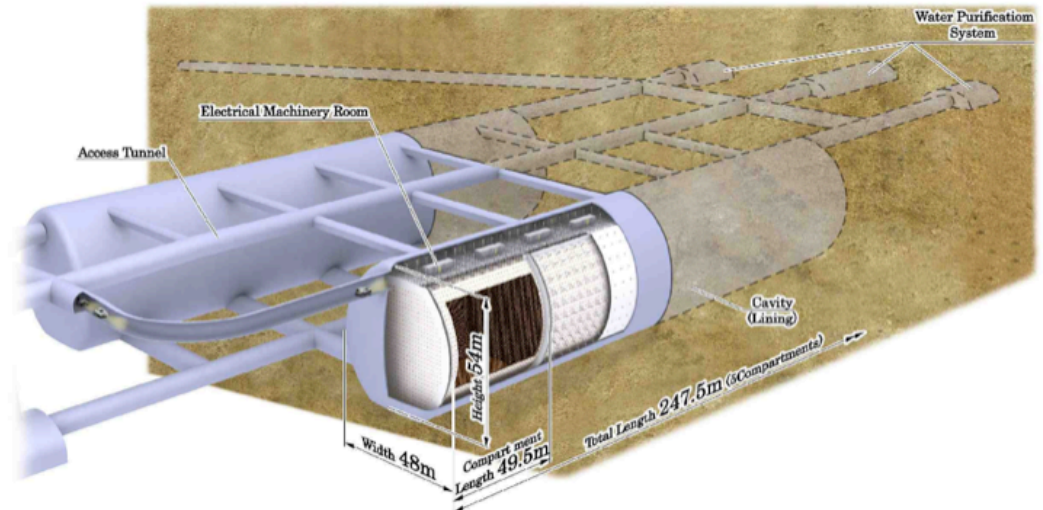
LENA



MEMPHYS

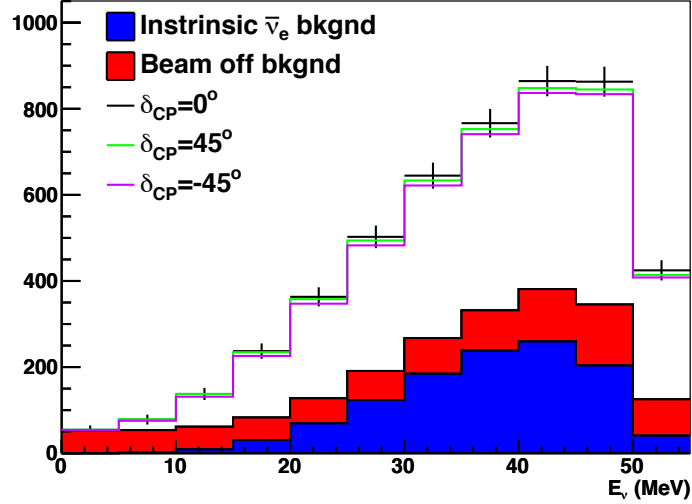
Hyper-K (or initially, Super-K)

Focus of this talk

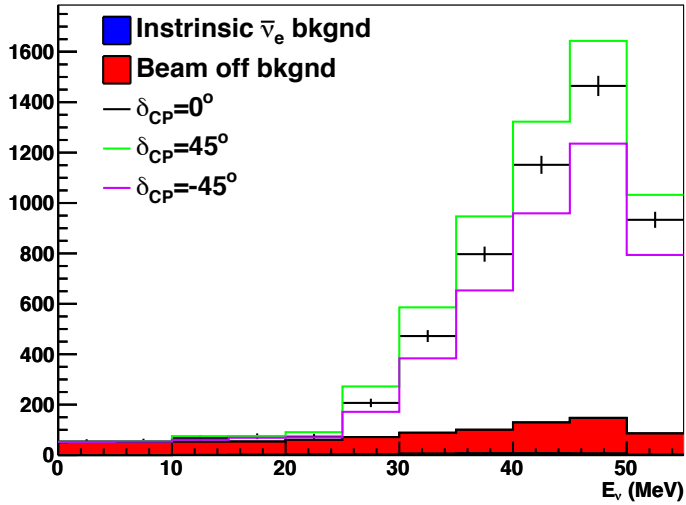


DAEδALUS@Hyper-K Events

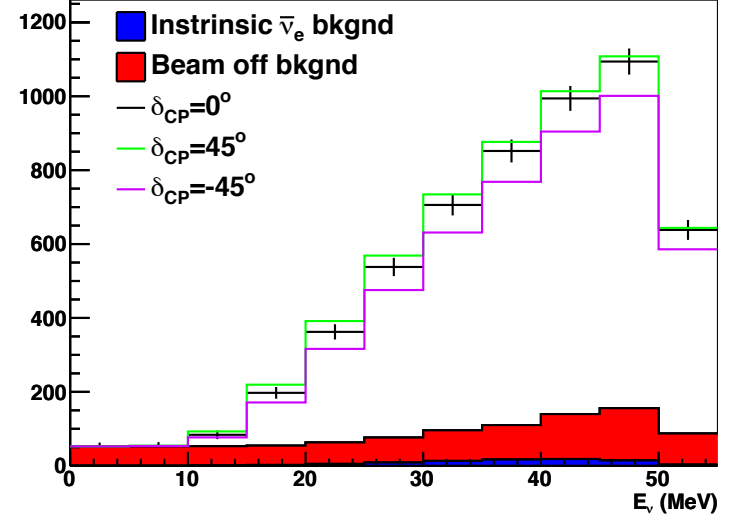
DAEdALUS@HyperK 1.5km Data



DAEdALUS@HyperK 20km Data

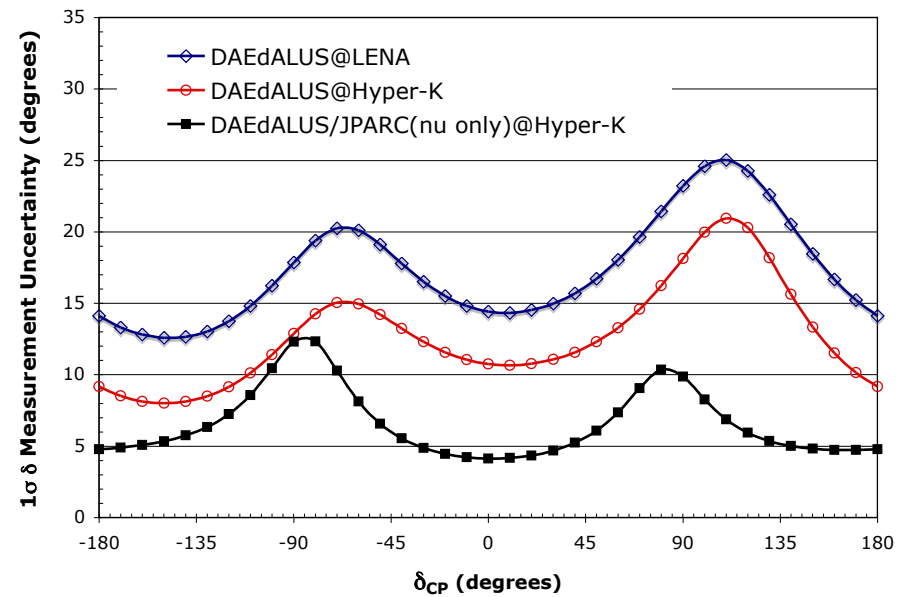
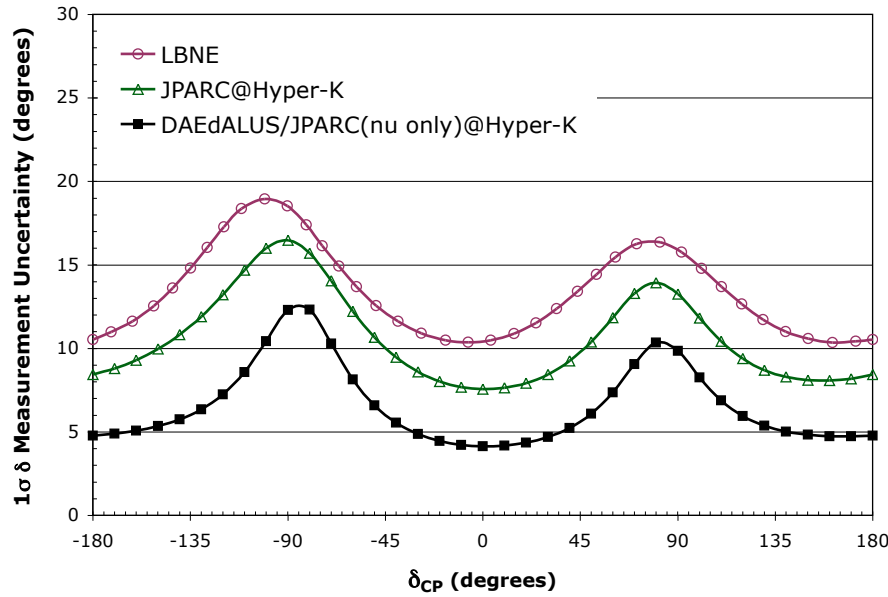


DAEdALUS@HyperK 8km Data



Event Type	1.5 km	8 km	20 km
IBD Oscillation Events ($E_{vis} > 20$ MeV)			
$\delta_{CP} = 0^\circ$, Normal Hierarchy	2660	4456	4417
" , Inverted Hierarchy	1838	3268	4338
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IBD from Intrinsic $\bar{\nu}_e$ ($E_{vis} > 20$ MeV)	1119	79	31
IBD Non-Beam ($E_{vis} > 20$ MeV)			
atmospheric $\nu_{\mu p}$ "invisible muons"	505	505	505
atmospheric IBD	103	103	103
diffuse SN neutrinos	43	43	43
ν -e Elastic ($E_{vis} > 10$ MeV)	40025	2813	1123
ν_e -oxygen ($E_{vis} > 20$ MeV)	188939	13281	5305

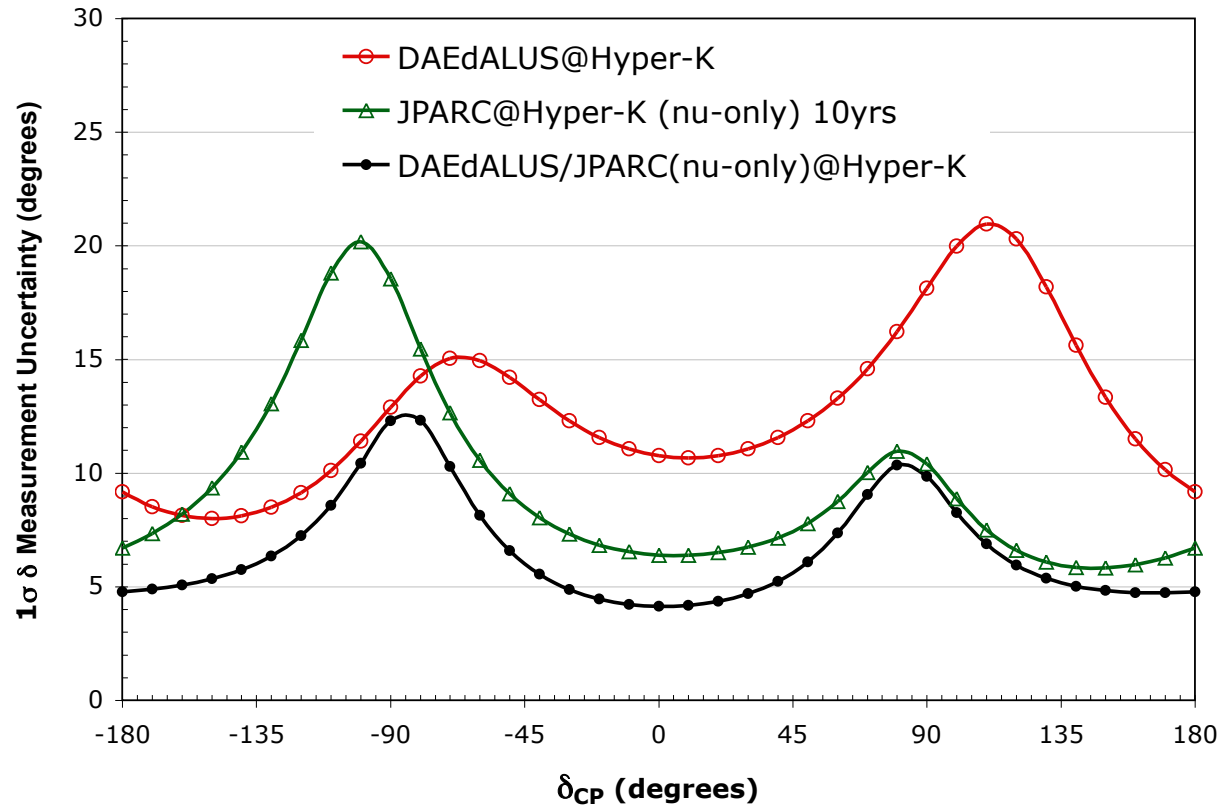
Sensitivity to δ_{CP} to 5°



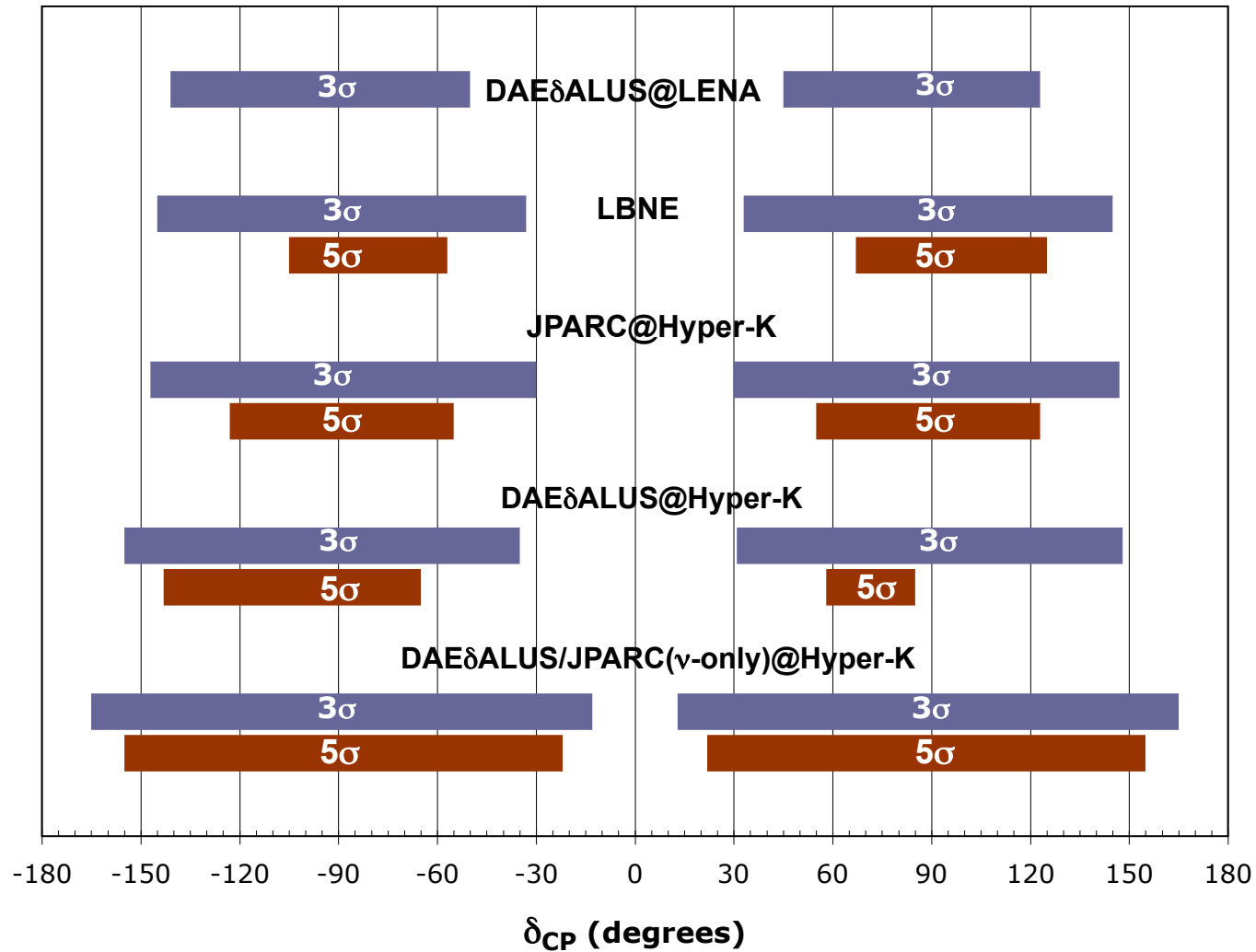
Configuration Name	Source(s)	Average Long Baseline Beam Power	Detector	Fiducial Volume	Run Length
DAE δ ALUS@LENA	DAE δ ALUS only	N/A	LENA	50 kt	10 years
DAE δ ALUS@Hyper-K	DAE δ ALUS only	N/A	Hyper-K	560 kt	10 years
DAE δ ALUS/JPARC (nu only)@Hyper-K	DAE δ ALUS & JPARC	750 kW	Hyper-K	560 kt	10 years
JPARC@Hyper-K	JPARC	750 kW	Hyper-K	560 kt	3 years ν + 7 years $\bar{\nu}$
LBNE	FNAL	850 kW	LBNE	35 kt	5 years ν 5 years $\bar{\nu}$

DAE δ ALUS/JPARC@Hyper-K

Complementarity

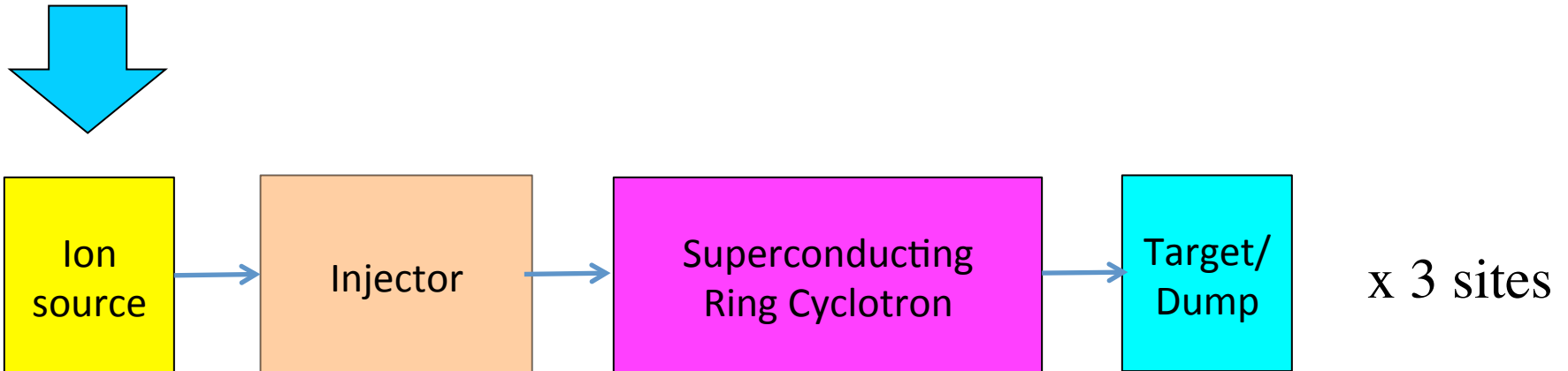


δ_{CP} Discovery Potential



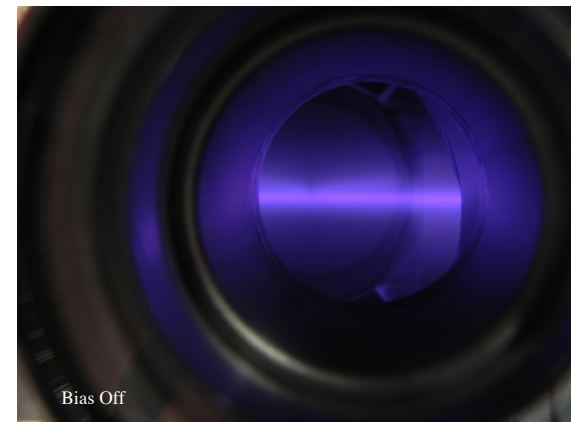
A Phased Approach to DAE δ ALUS

Phase I

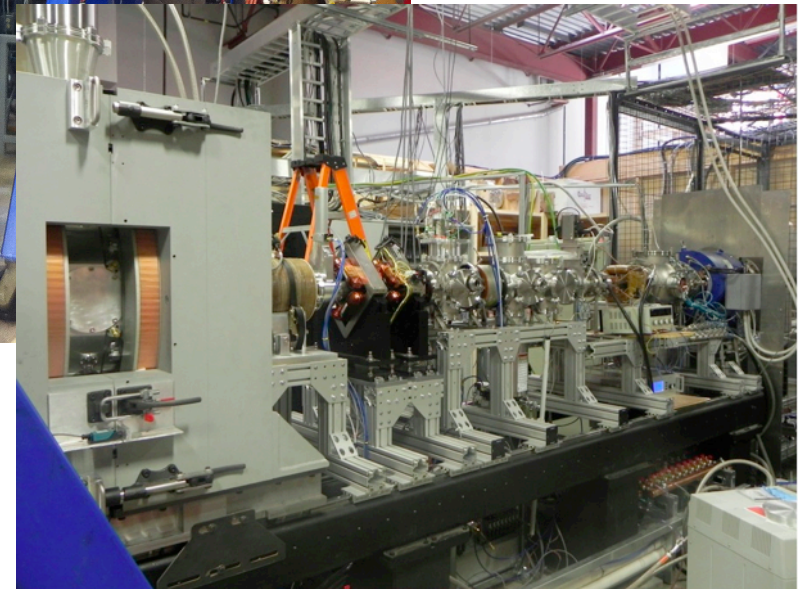
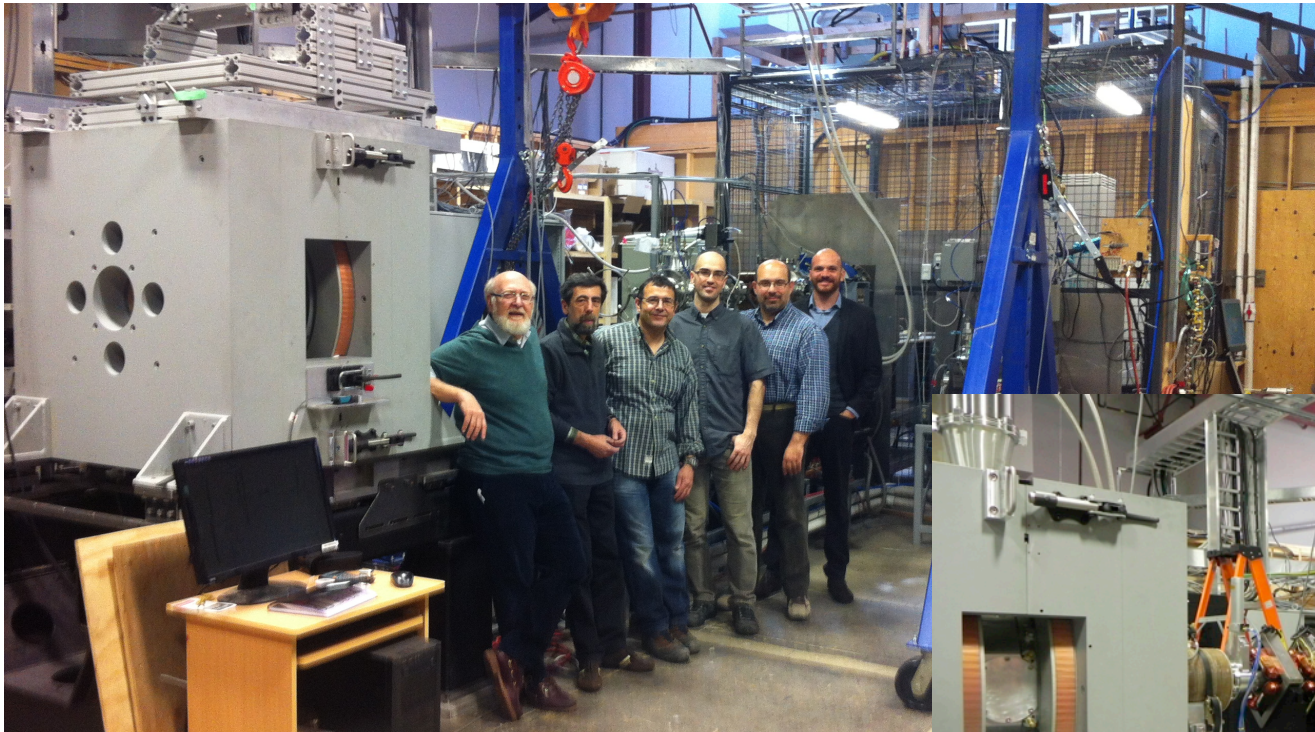


Tests of Versatile Ion Source (VIS)*
at Best Cyclotrons, Inc.

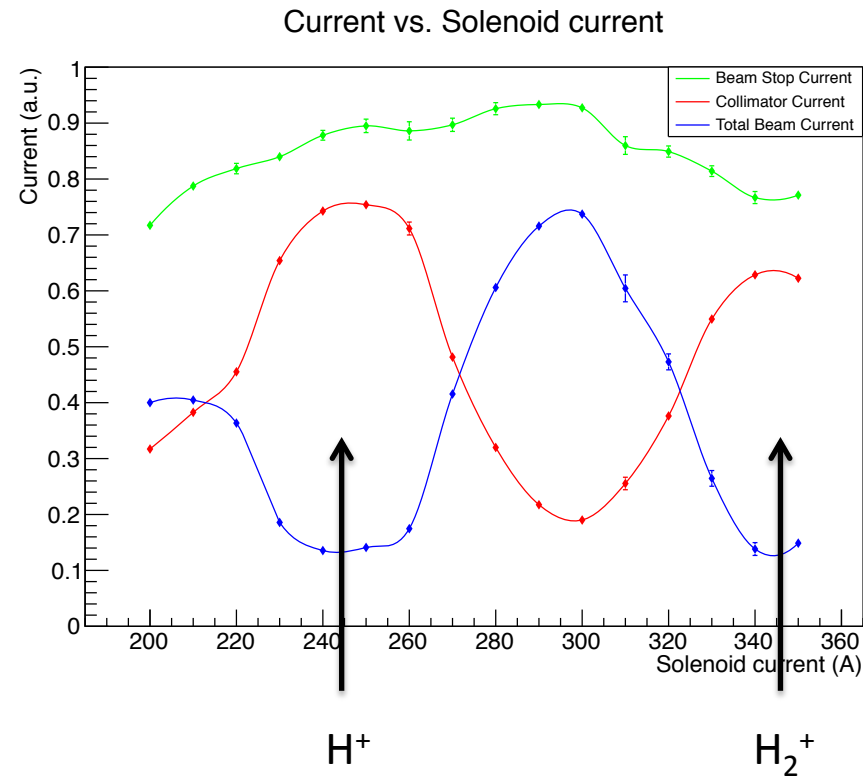
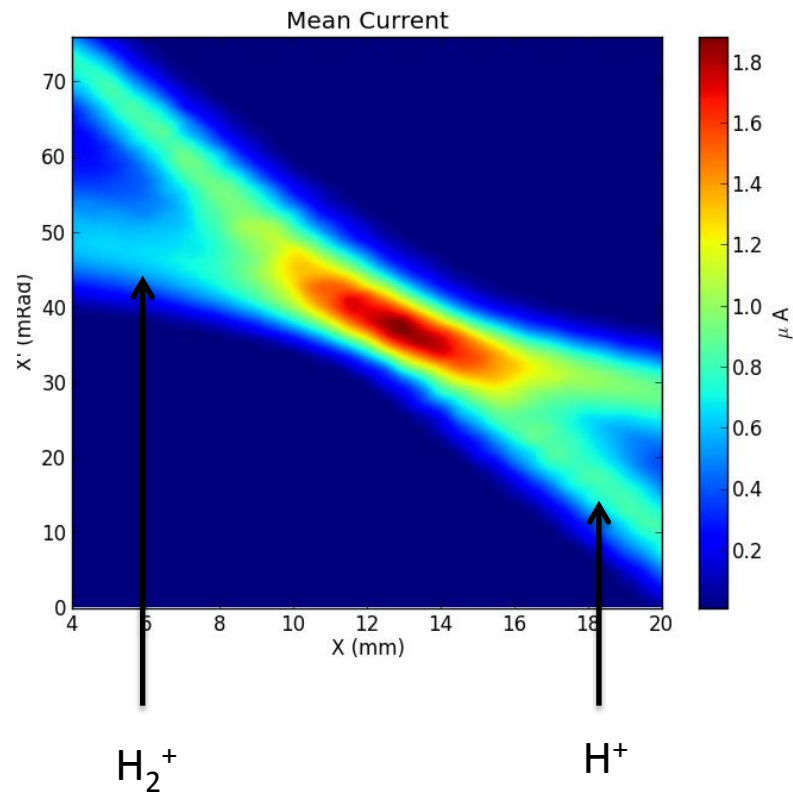
*S. Gammino et al., "Tests of the Versatile Ion Source (VIS) for high power proton beam production", ECRIS'10, Grenoble, France



International Partnership Between Universities, Labs, and Industry



Beam Characterization Ongoing

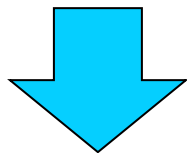
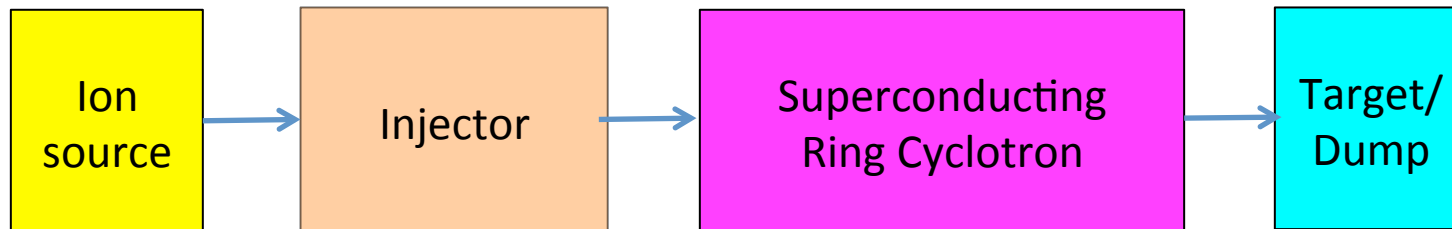
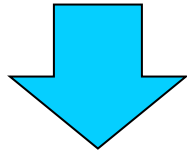


Industry Interest: Medical Isotopes

Isotope	half-life	Use
^{52}Fe	8.3 h	The parent of the PET isotope ^{52}Mn and iron tracer for red-blood-cell formation and brain uptake studies.
^{122}Xe	20.1 h	The parent of PET isotope ^{122}I used to study brain blood-flow.
^{28}Mg	21 h	A tracer that can be used for bone studies, analogous to calcium
^{128}Ba	2.43 d	The parent of positron emitter ^{128}Cs . As a potassium analog, this is used for heart and blood-flow imaging.
^{97}Ru	2.79 d	A γ -emitter used for spinal fluid and liver studies.
^{117m}Sn	13.6 d	A γ -emitter potentially useful for bone studies.
^{82}Sr	25.4 d	The parent of positron emitter ^{82}Rb , a potassium analogue This isotope is also directly used as a PET isotope for heart imaging.

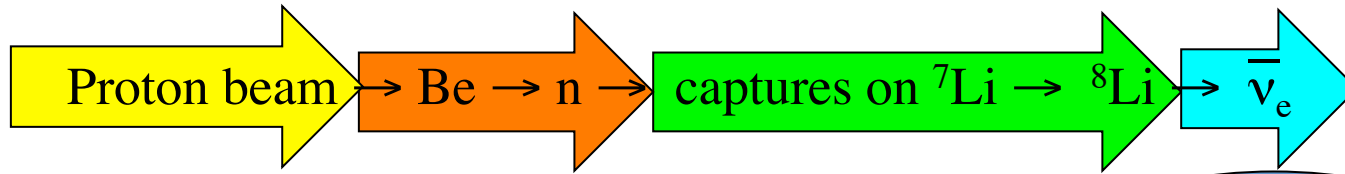
A Phased Approach to DAE δ ALUS

Phase II

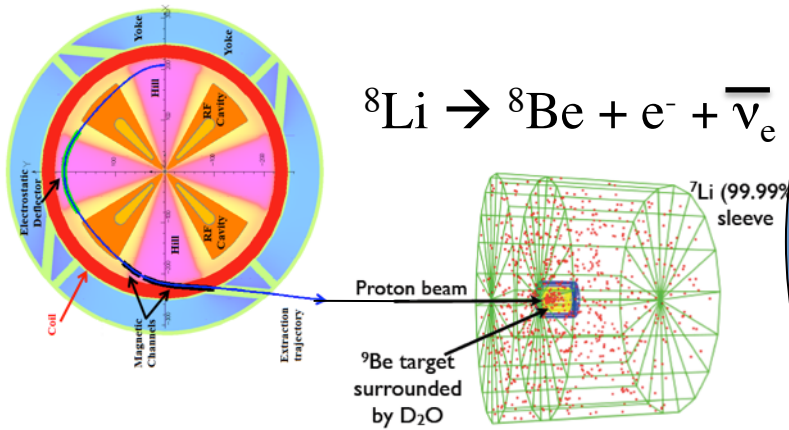


IsoDAR^{*}: A sterile neutrino experiment

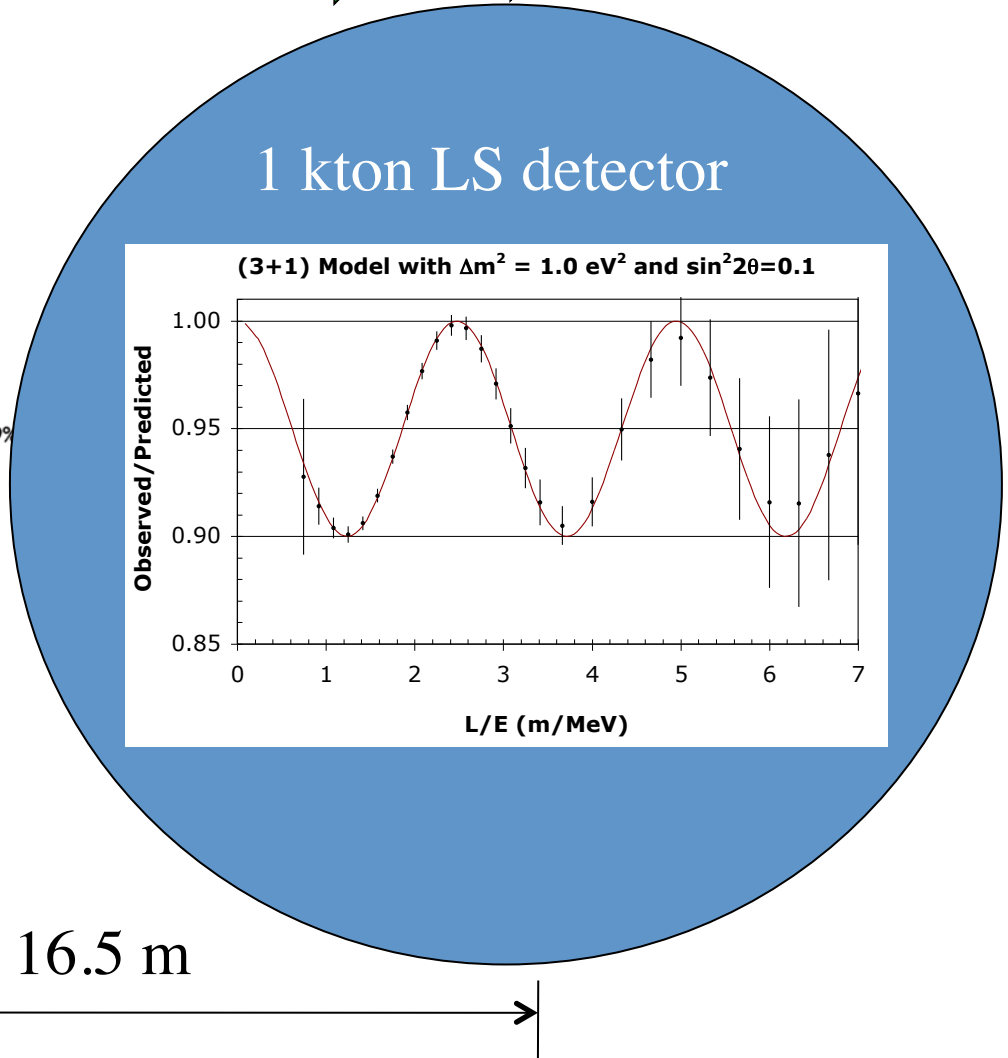
** PRL 109, 141802 (2012)*



Accelerates 5mA H_2^+
to 60 MeV/amu



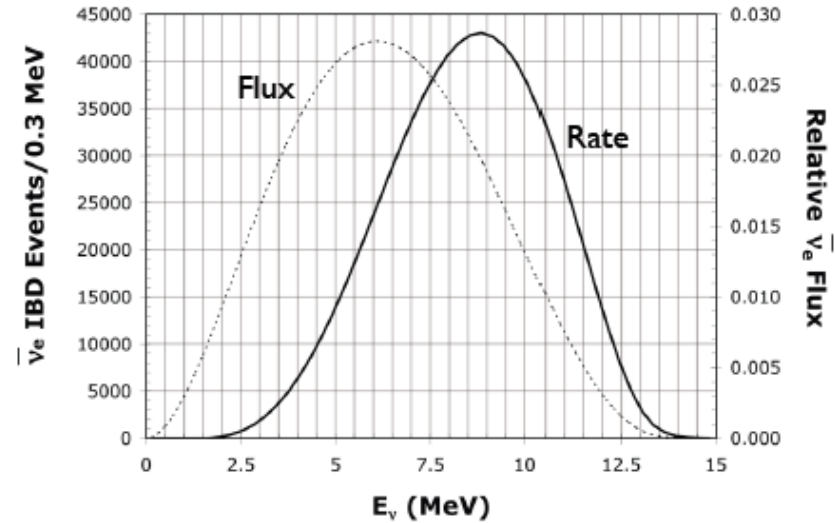
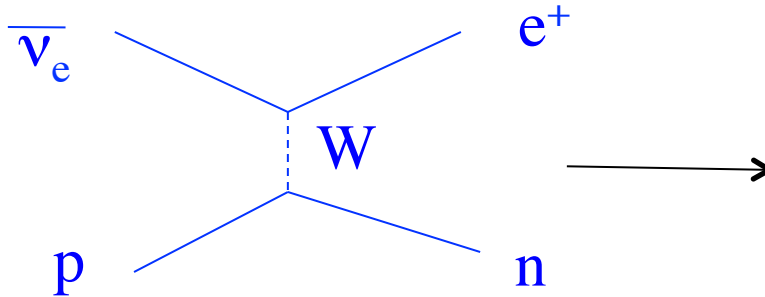
Not to scale



Potential location: KamLAND

Five Years of Running at KamLAND

Inverse β Decay (IBD)



Accelerator	60 MeV/amu of H_2^+
Current	10 mA of protons on target
Power	600 kW
Duty cycle	90%
Run period	5 years (4.5 years live time)
Target	^9Be surrounded by ^7Li (99.99%)
$\bar{\nu}$ source	^8Li β decay ($\langle E_\nu \rangle = 6.4$ MeV)
$\bar{\nu}_e/1000$ protons	14.6
$\bar{\nu}_e$ flux	$1.29 \times 10^{23} \bar{\nu}_e$
Detector	KamLAND
Fiducial mass	897 tons
Target face to detector center	16 m
Detection efficiency	92%
Vertex resolution	$12 \text{ cm}/\sqrt{E} \text{ (MeV)}$
Energy resolution	$6.4\%/\sqrt{E} \text{ (MeV)}$
Prompt energy threshold	3 MeV
IBD event total	8.2×10^5
$\bar{\nu}_e$ -electron event total	7200

820,000 IBD events

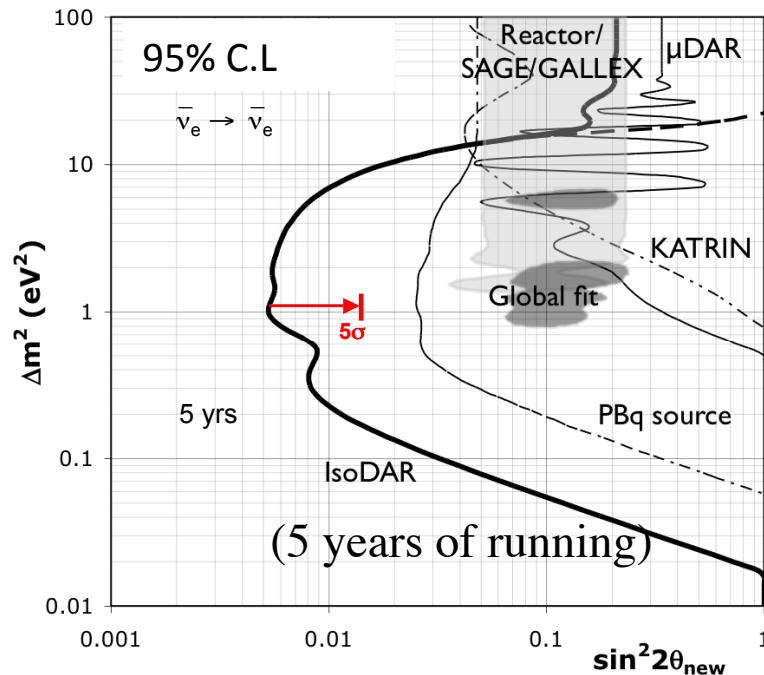
➤ **Sterile neutrino search**

7,200 $\bar{\nu}_e$ -electron events

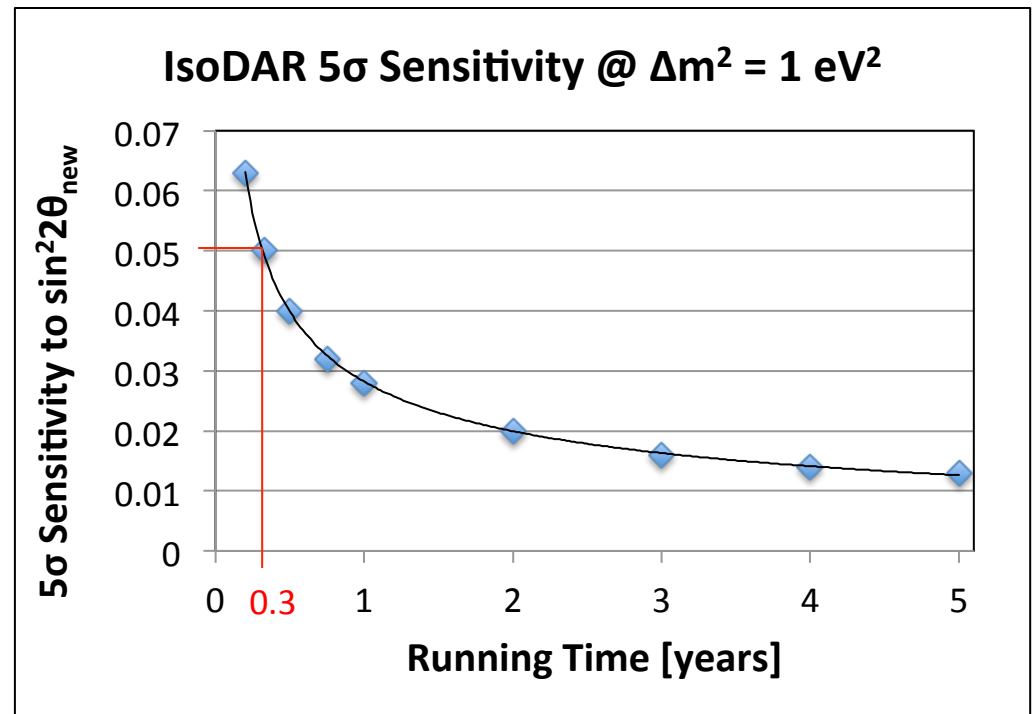
➤ Measure $\sin^2\theta_w$ to 3.2%

➤ Probe weak couplings and nonstandard interactions (NSIs)

Outstanding sensitivity to sterile neutrinos à la the reactor neutrino anomaly...

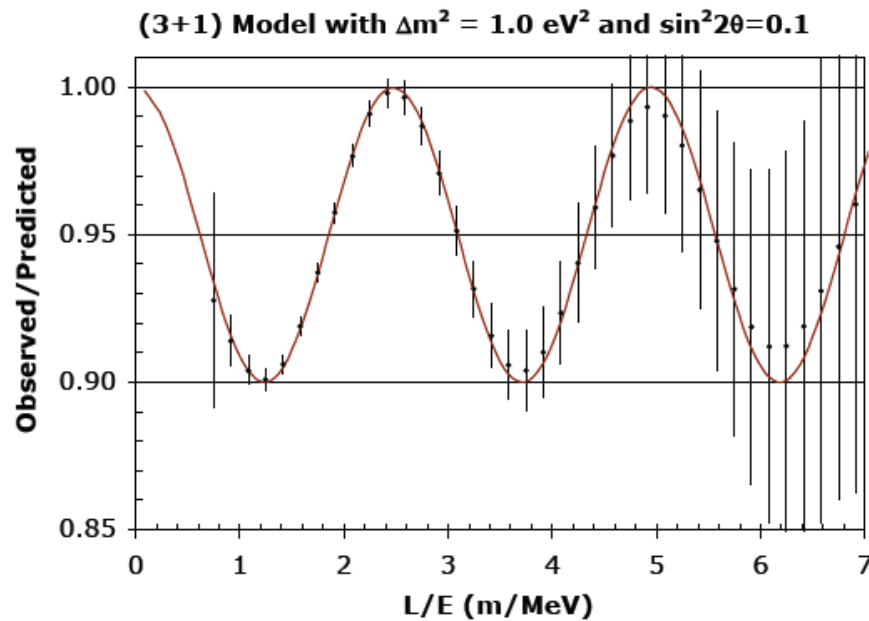


In fact, global fit can be ruled out at $> 5\sigma$ in 4 months of running!

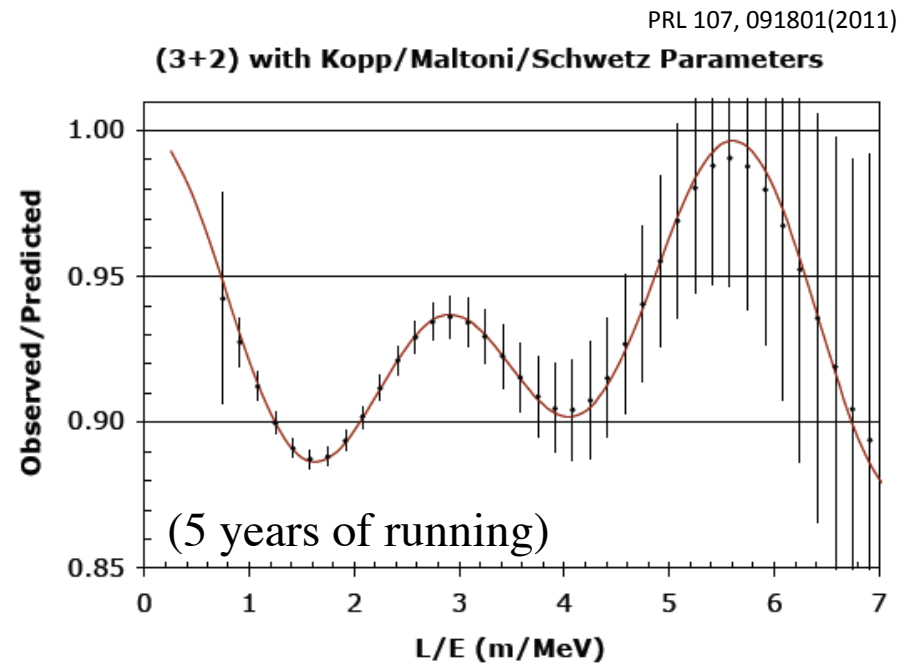


IsoDAR can also **discriminate** between different sterile neutrino **models**!

3+1

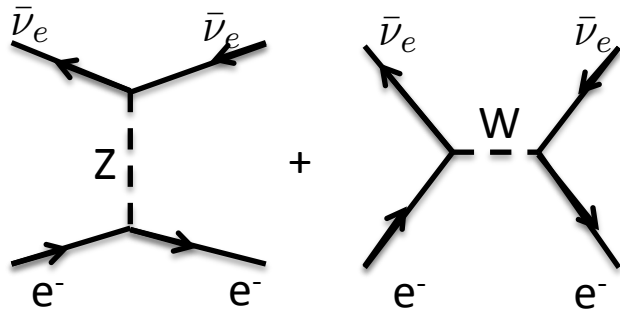


3+2



Precision $\bar{\nu}_e e$ Electroweak Measurements

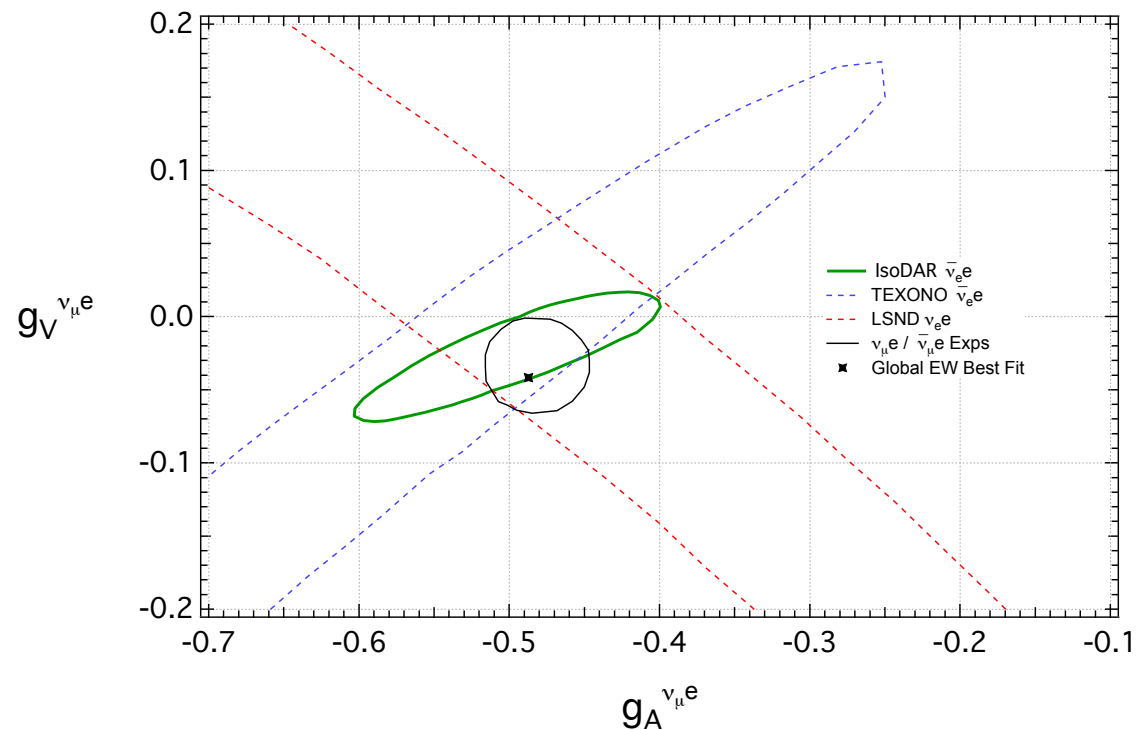
7,200 $\nu_e e$ events in 5 years of running



$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi} \left[g_R^2 + g_L^2 \left(1 - \frac{T}{E_\nu}\right)^2 - g_R g_L \frac{m_e T}{E_\nu^2} \right]$$

$$g_R = \frac{1}{2}(g_V - g_A)$$

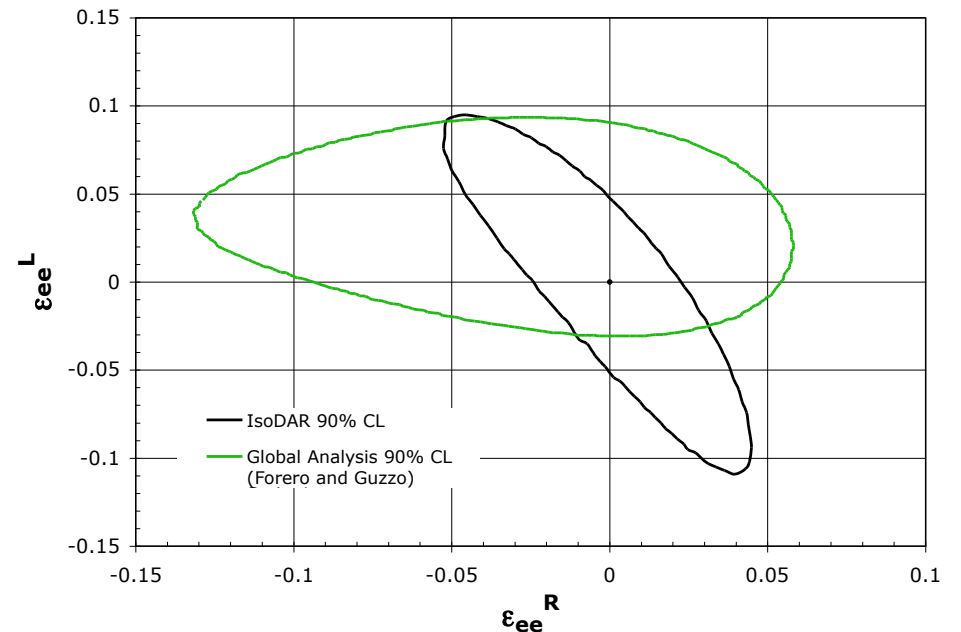
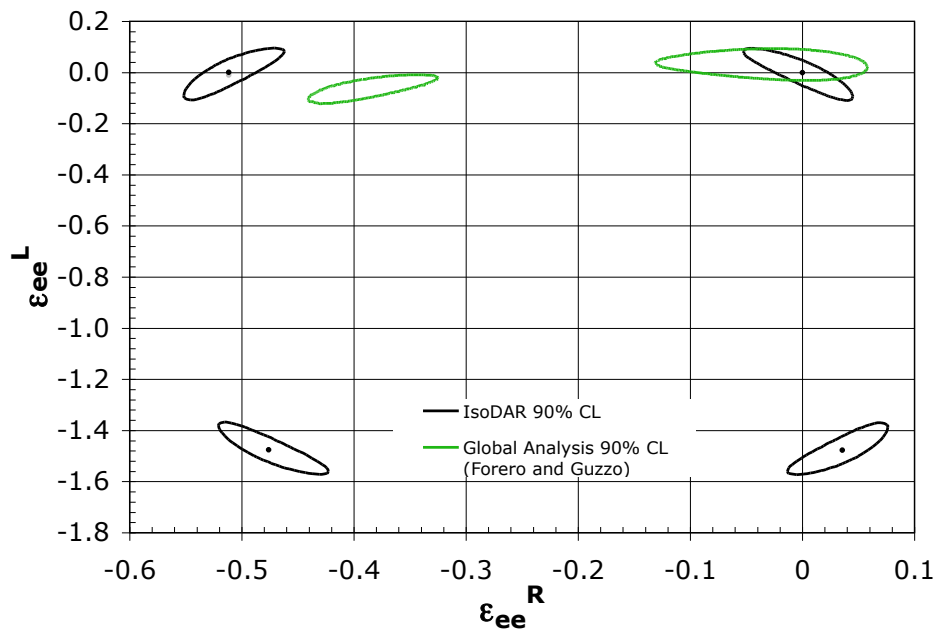
$$g_L = \frac{1}{2}(g_V + g_A)$$

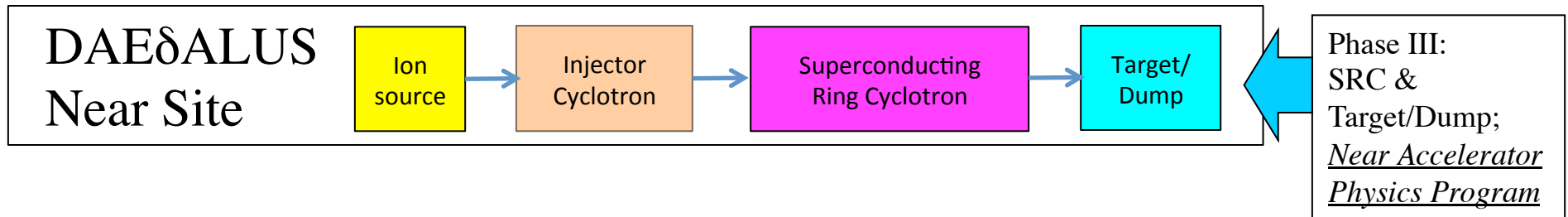


Non-standard Interactions

$$g_L \longrightarrow g_L + \epsilon_{ee}^{eL}$$

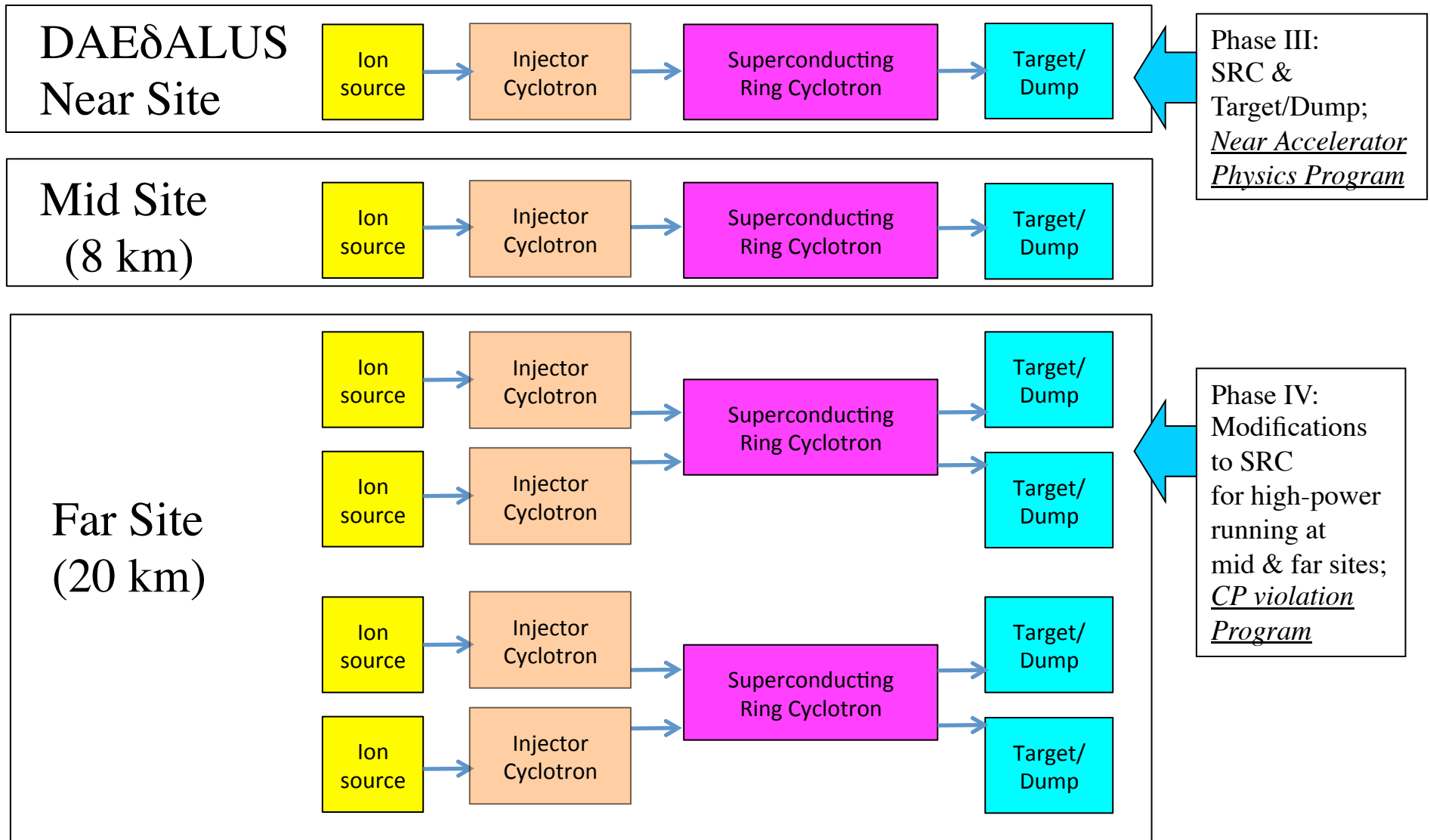
$$g_R \longrightarrow g_R + \epsilon_{ee}^{eR}$$



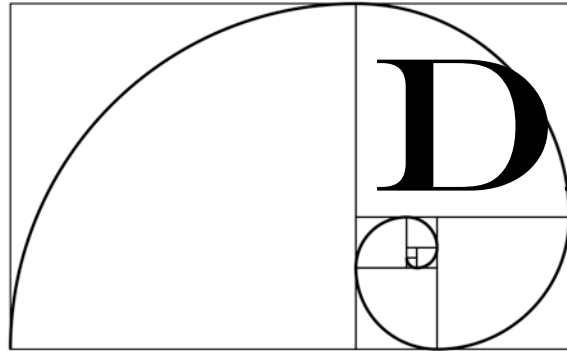


Many exciting possibilities for a near accelerator physics program:

- Short-baseline neutrino oscillation waves in ultra-large liquid scintillator detectors
Agarwalla, S. et. al. JHEP 12 (2011), 85
- Coherent neutrino scattering in dark matter detectors
Anderson A., et. al. Phys. Rev. D 84, 013008 (2011)
- Active-to-sterile neutrino oscillations with neutral current coherent neutrino scattering
Anderson, A. et. al. Phys. Rev. D 86, 013004 (2012)
- Measurement of the weak mixing angle with neutrino-electron scattering at low energy
Agarwalla, S. and P. Huber JHEP 8 (2011), 59



Conclusions



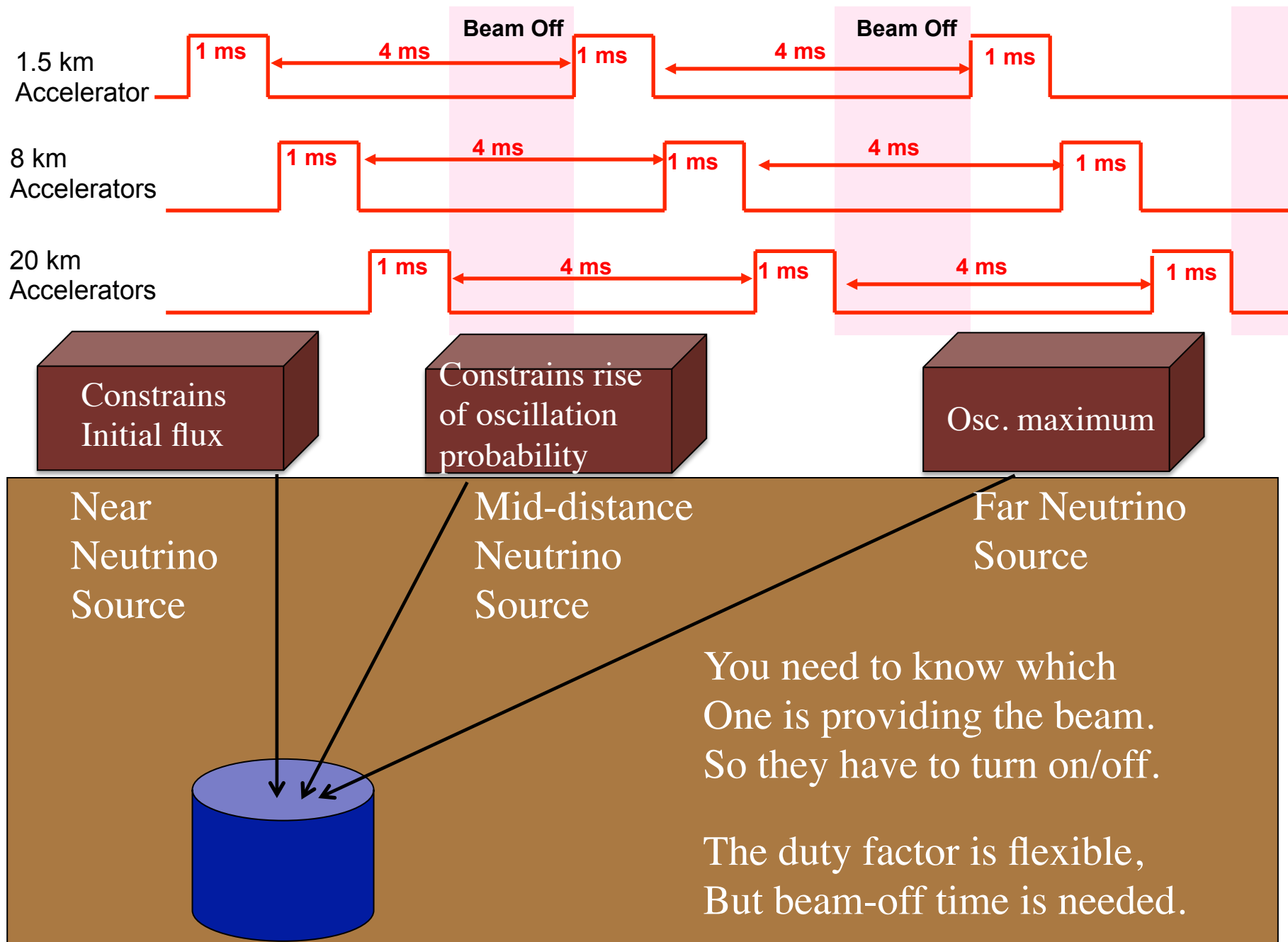
DAE δ ALUS

Has superb sensitivity to δ_{CP} extending down 5°

Is a phased program with strong physics along the way
(especially the IsoDAR sterile neutrino search!)

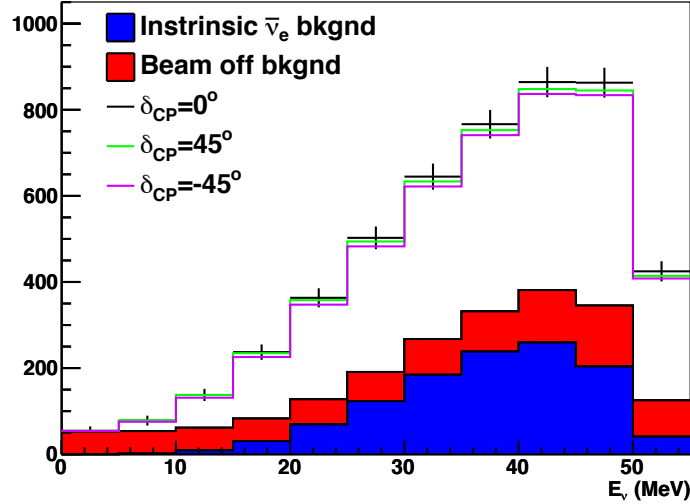
Being brought to you by an international collaboration
of accelerator and particle physicists,
with input from Industry

Backup

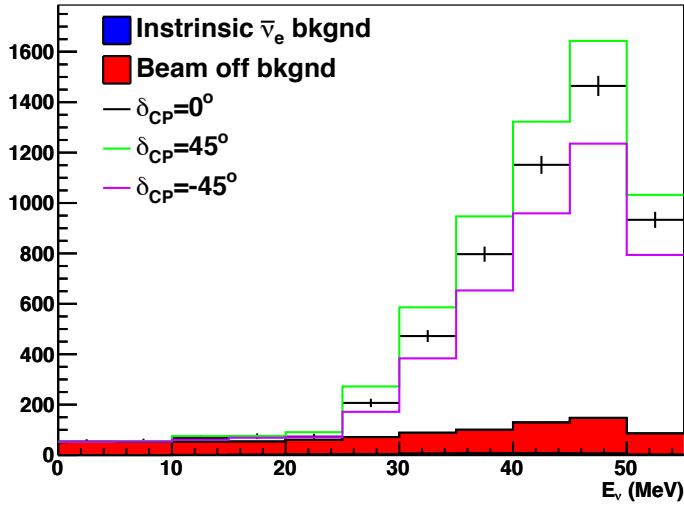


DAE δ ALUS@Hyper-K Events

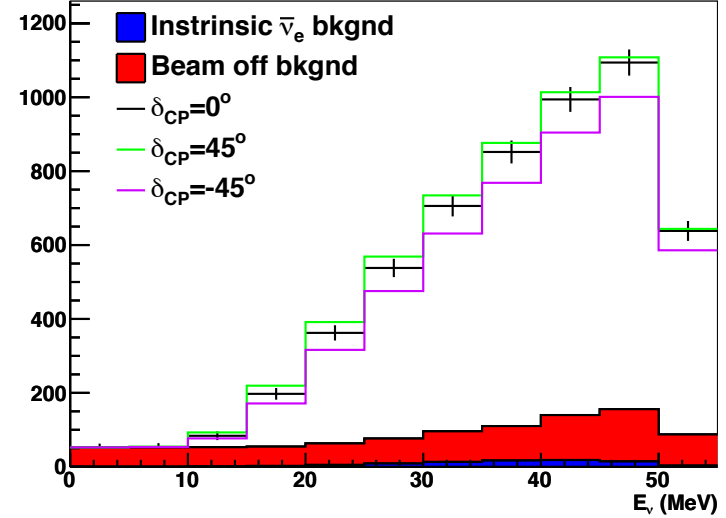
DAEdALUS@HyperK 1.5km Data



DAEdALUS@HyperK 20km Data



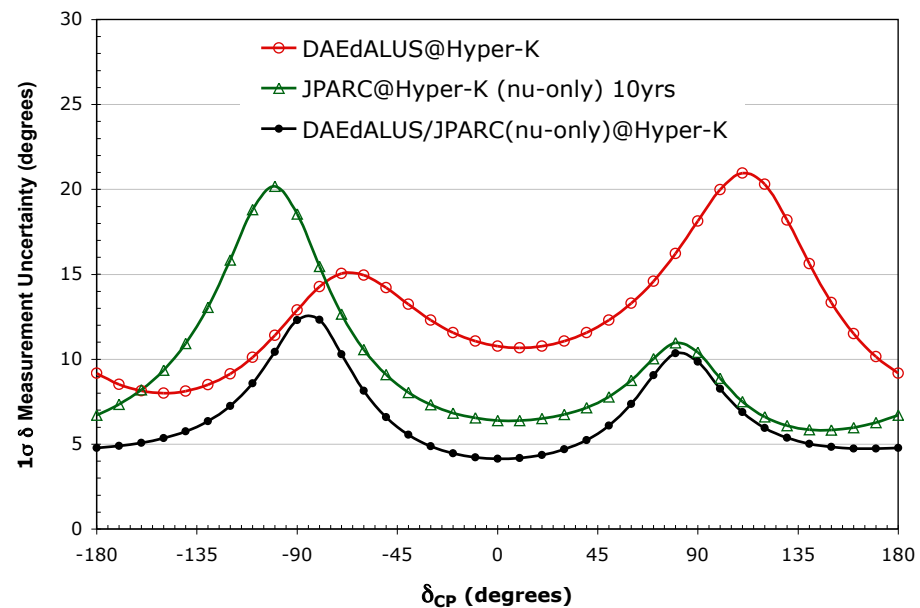
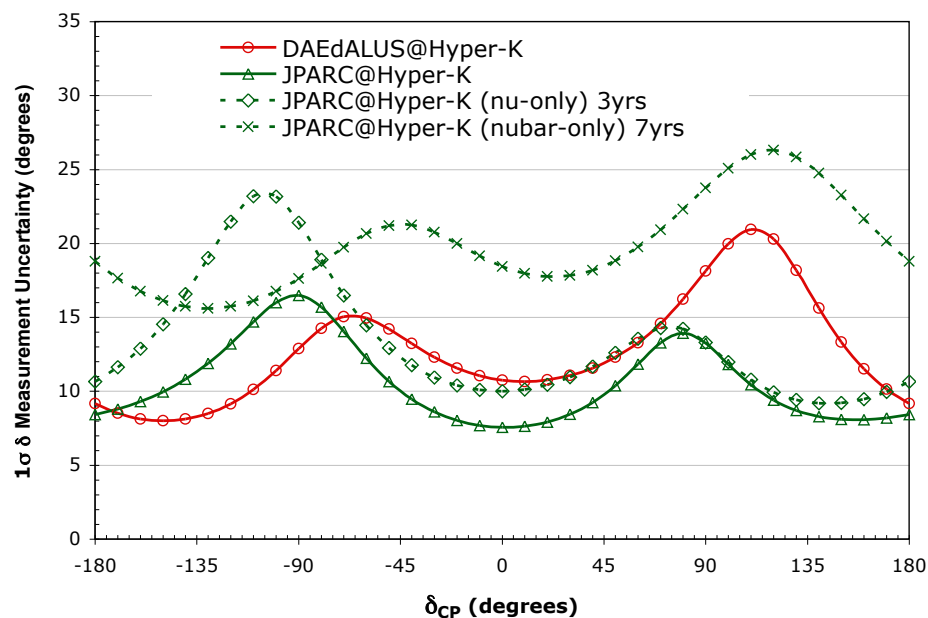
DAEdALUS@HyperK 8km Data



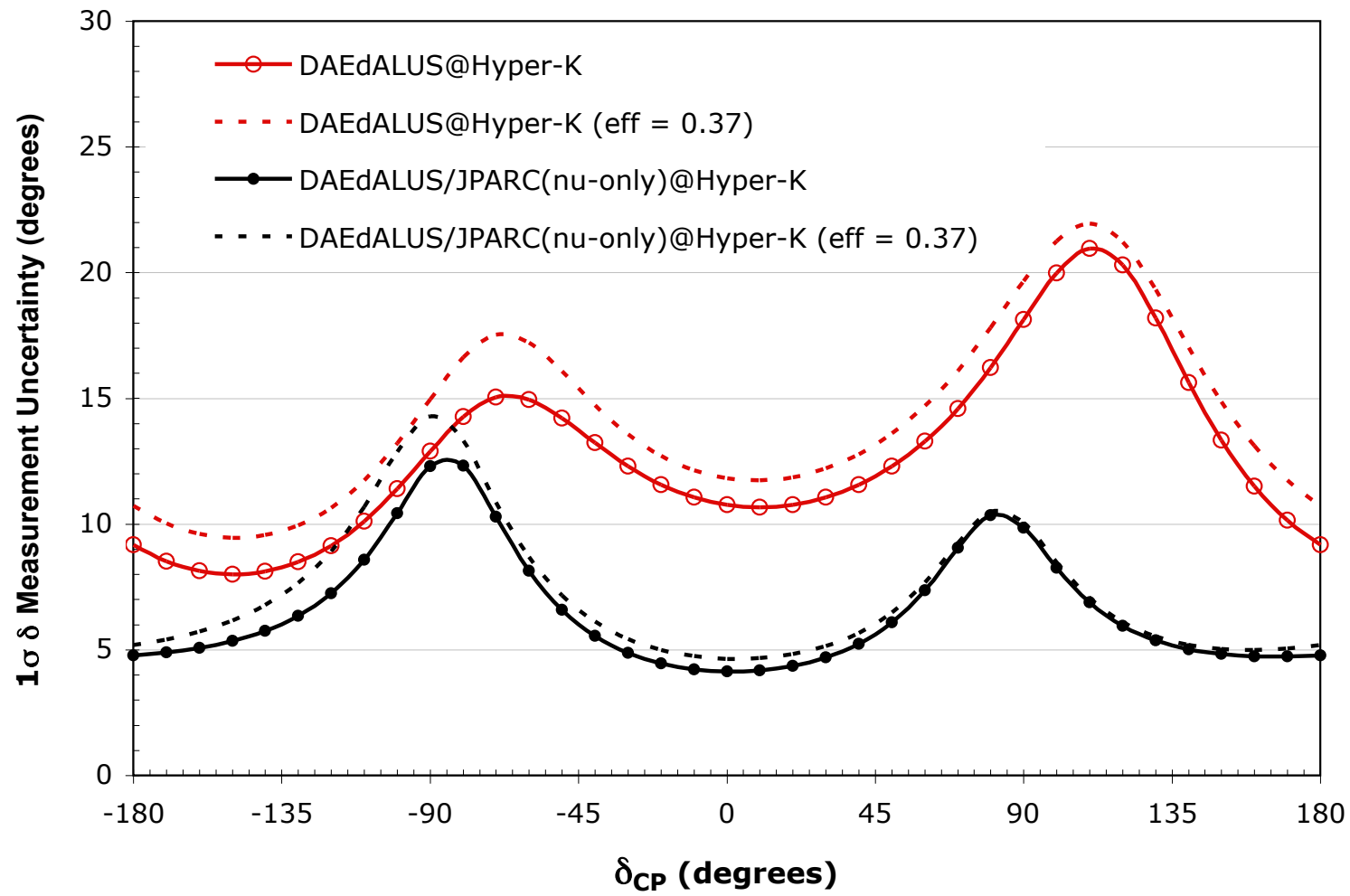
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DAEdALUS/JPARC@Hyper-K

Complementarity



$$\epsilon_{\text{IBD}} = 67\% \text{ vs. } \epsilon_{\text{IBD}} = 37\%$$



Our proposed 800 MeV super-conducting ring cyclotron is very similar to the existing Riken, Japan, cyclotron:

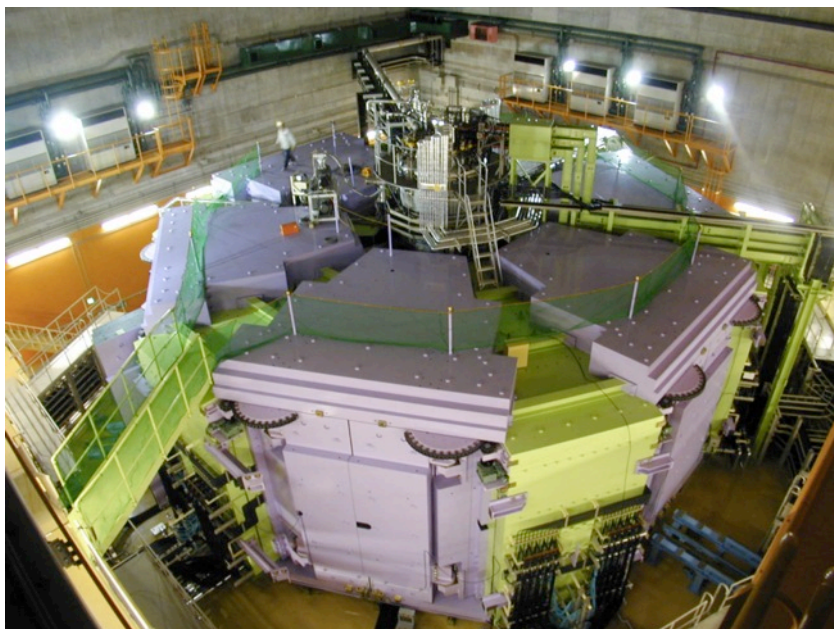


Table 5: Comparison of main parameters for DSRC with those for RIKEN-SRC

Basic Parameters	DSRC	RIKEN-SRC	Unit
Maximum field on the hill	6.05	3.8	T
Maximum field on the coil	6.18	4.2	T
Stored Energy	280	235	MJ
Coil size	30× 24 or 15× 48	21× 28	cm ²
Coil Circumference	9.8	10.86	m
Magnetomotive force	4.9	4	MA _{tot} /sector
Current density	34	34	A/mm ²
Height	5.6	6.0	m
Length	6.9	7.2	m
Weight	≤450	800	ton
Additional magnetic shield	0	3000	ton/total
Magnetic Forces			
Expansion	1.87 or 1.8	2.6	MN/m
Vertical	3.7	3.3	MN
Radial shifting	2.7	0.36	MN
Azimuthal shifting	0.2	0	MN
Force on the pole	tbd	630	MN
Main Coil			
Operational current	5000	5000	A
Layer × turn	31×16	22×18	
Cooling	Bath cooling	Bath cooling	
Maddock Stabilized Current	6345	6665	A
Other Components			
SC trim	no	4	sets
NC trim× turn	no	22	pairs
Stray field in the SRC valley region	0.01	0.04	T
Gap for thermal insulation	40	90@min.	mm
Extraction method	Stripper foil	Electrostatic channel	

Our first engineering design from MIT-PFSC Technology and Engineering Division:

arXiv.org > physics > arXiv:1209.4886 Search or

Physics > Accelerator Physics

Engineering Study of Sector Magnet for the Daedalus Experiment

(Joseph Minervini) Mike Cheadle, Val Fishman, Craig Miller, Alexi Radovinsky, Brad Smith

(Submitted on 21 Sep 2012)

The Daedalus experiment seeks to evaluate neutrino scattering effects that go beyond the standard model. Modular accelerators are employed to produce 800 MeV proton beams at the megawatt power level directed toward a target, producing neutrinos. The Superconducting Ring Cyclotron (SRC) consists of identical sectors (currently 6) of superconducting dipole magnets with iron return frames. The Daedalus Collaboration has chosen a conceptual design for the magnet which meets several requirements: the most best design that achieves the physics requirements of the experiment. The Technology and Engineering Division (TED) of the MIT Plasma Science and Fusion Center was awarded with a contract by the Daedalus team to further develop the magnet conceptual design. The resulting Engineering Study is reported here.

Winner of the 2013 IEEE Council on Superconductivity Award!

Design work
By A. Calanna

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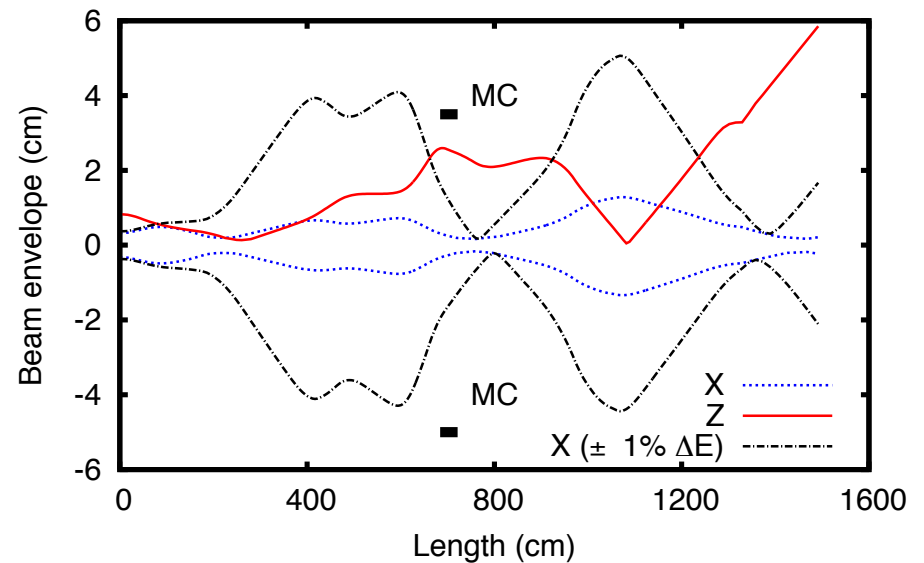
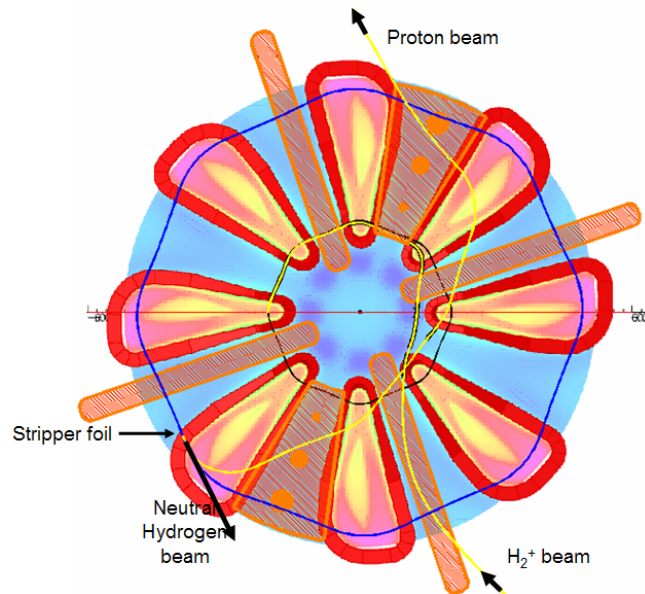
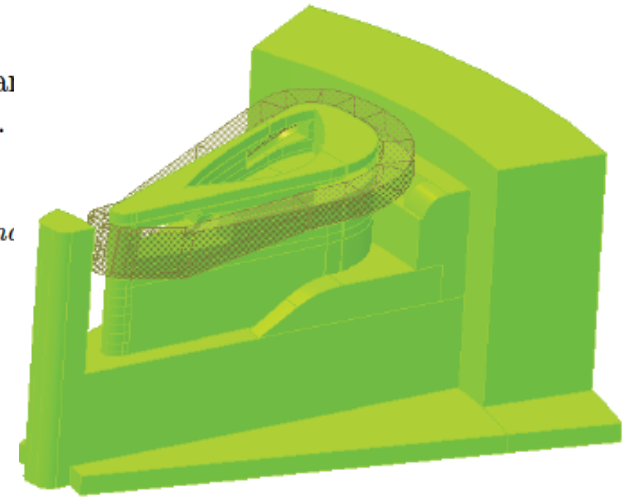
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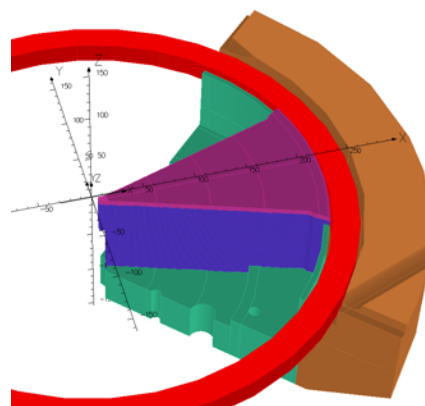
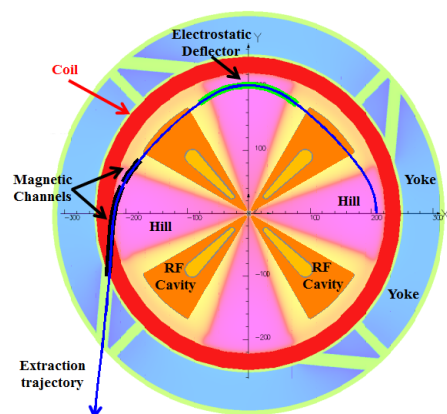
^jIDA Research



Injector Cyclotron

- Non-superconducting, single coil design
- Accelerates 5mA H_2^+ to 60 MeV/amu (600 kW proton beam)
- Beam dynamics simulated using OPAL code
 - Verified single turn extraction with ‘classical’ electrostatic septum

[Phys. Rev. ST Accel.
Beams 13, 064201 (2010)]



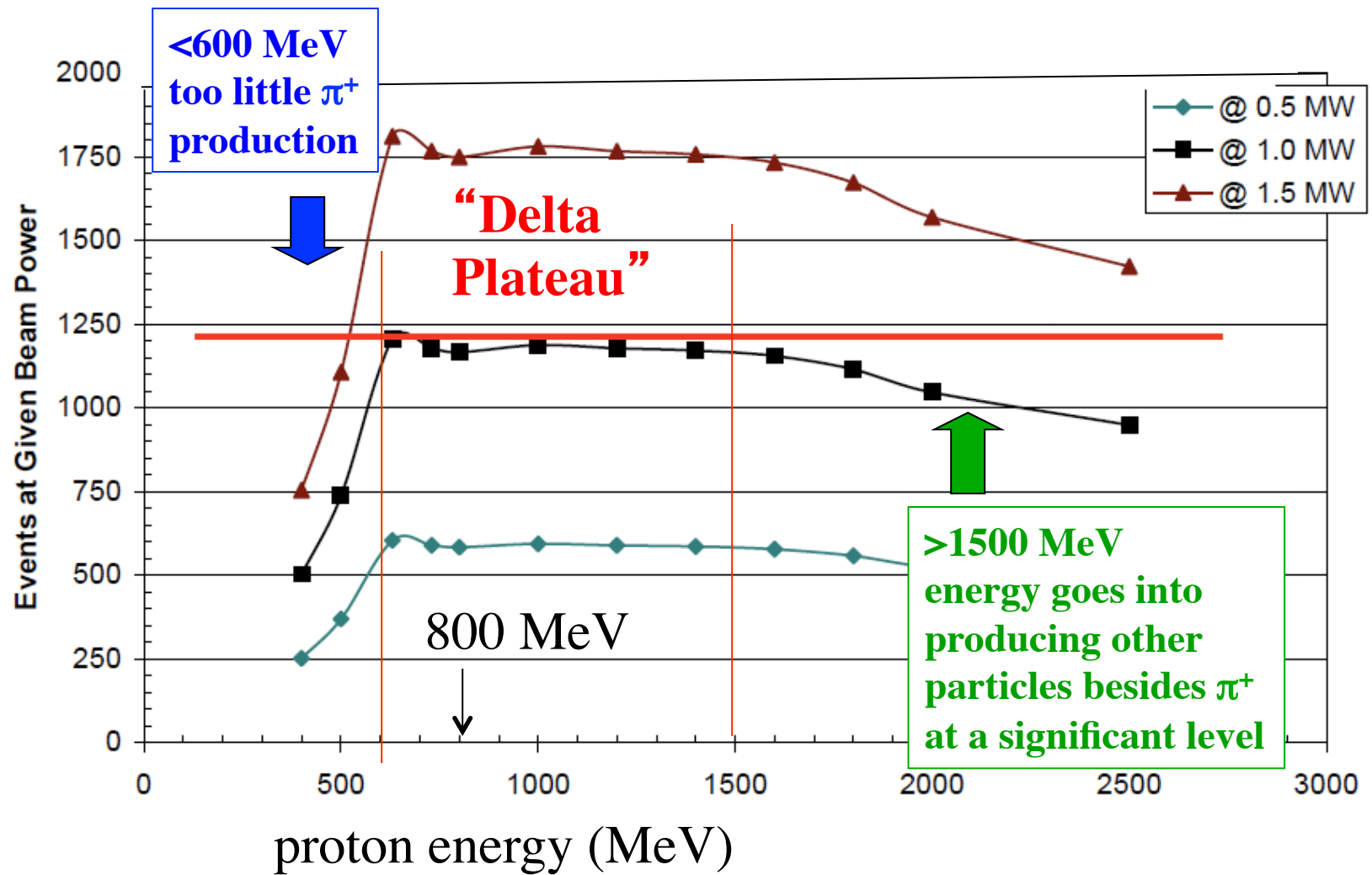
E_{max}	60 MeV/amu	E_{inj}	35 keV/amu
R_{ext}	1.99 m	R_{inj}	55 mm
$\langle B \rangle @ R_{ext}$	1.16 T	$\langle B \rangle @ R_{inj}$	0.97 T
Sectors	4	Hill width	28 - 40 deg
Valley gap	1800 mm	Pole gap	100 mm
Outer Diameter	6.2 m	Full height	2.7 m
Cavities	4	Cavity type	$\lambda/2$, double gap
Harmonic	6th	rf frequency	49.2 MHz
Acc. Voltage	70 - 240 kV	Power/cavity	310 kW
$\Delta E/\text{turn}$	1.3 MeV	Turns	95
$\Delta R/\text{turn} @ R_{ext}$	> 14 mm	$\Delta R/\text{turn} @ R_{inj}$	> 56 mm
Coil size	200x250 mm ²	Current density	3.1 A/mm ²
Iron weight	450 tons	Vacuum	< 10 ⁻⁷ mbar

Comparison of IsoDAR to alternative designs

Assessment		IsoDAR Base Design	RFQ/Separated Sector Cyclotron	LINAC, 30 MeV, 40 mA	Modified Beta Beam Design	New Detector at Existing Beam
1. Cost		Good	Moderate	Bad	Moderate	Bad
2. $\bar{\nu}_e$ rate		Good	Good	Good	Bad	Good
3. Backgrounds low		Good	Good	Good	Good	Moderate
4. Technical risk		Moderate	Moderate	Moderate	Moderate	Good
5. Compactness		Good	Moderate	Bad	Good	Moderate
6. Simplicity u'ground		Good	Moderate	Moderate	Bad	Moderate
7. Reliability		Good	Good	Good	Bad	Good
8. Value to other exps		Good	Good	Good	Bad	Bad
9. Value to Industry		Good	Moderate	Moderate	Bad	Bad

What proton energy is required?

There is a “Delta plateau” where you can trade energy for current to get the same rate of ν/MW



Accelerator Collaborators and Participants*

- Collaboration Spokespersons:
 - Janet Conrad, MIT
 - Mike Shaevitz, Columbia
- Collaborating Laboratories (Support: Internal and MIT contracts)
 - Laboratori Nazionali del Sud (INFN-LNS), Catania, Italy
 - Luciano Calabretta, Alessandra Calanna, Daniela Campo, Luigi Celona, Santo Gammino, ...
 - Paul Scherrer Institute, Villigen, Switzerland
 - Andreas Adelmann, Jianjun Yang, Marco Schippers, ...
 - RIKEN, Wako, Saitama, Japan
 - Hiroki Okuno
- Industries (Support: Internal)
 - Best Cyclotron Systems, Vancouver BC
 - Bruce Milton, Todd Mawhinney, Francis Labecque, ...
 - IBA, Louvain la Neuve, Belgium
 - Yves Jongen, Willem Kleeven, Michel Abs, ...
 - AIMA, Nice, France
 - Pierre Mandrillon, Gerome Mandrillon
- Many Universities worldwide
 - See <http://www.nevis.columbia.edu/daedalus/collab/index.html>

* Principle funding provided by NSF through MIT

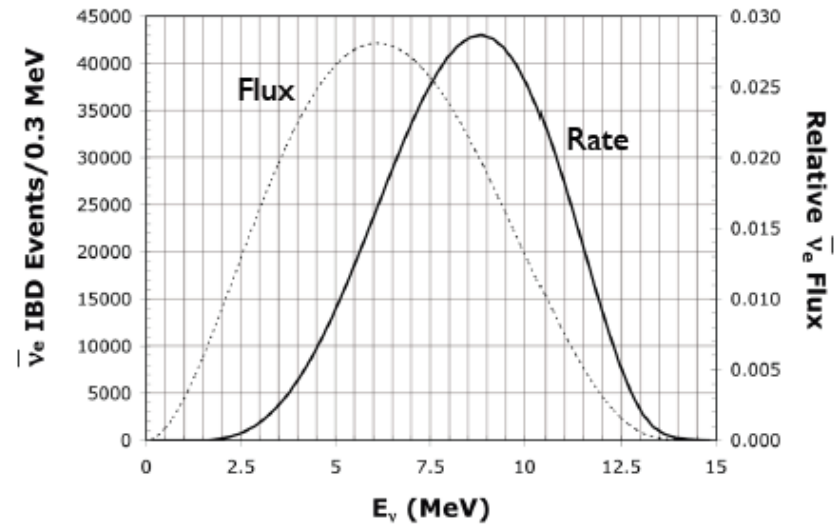
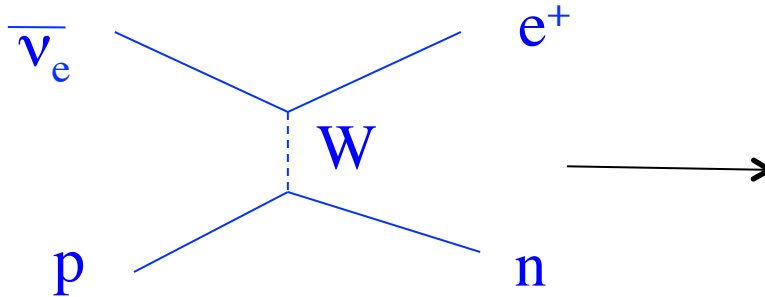
Accelerator Physicists and Engineers Involved in the Cyclotron Development

Adriana Bungau, University of Huddersfield
Alessandra Calanna, MIT
Anna Kolana, University of Huddersfield/PSI
Andreas Adelmann, PSI
Bernard Gottschalk, Harvard University
Bill Barletta, MIT
Bruce Milton, Best, Inc.
Chris Tschalaer, MIT
Daniel Winklehner, Michigan State University
Daniela Campo, MIT
Eric Forton, IBA-Research
Francis Labrecque, Best, Inc.
Hiroki Okunu, RIKEN
Hywel Owen, University of Manchester
Jerome Mandrillon, AIMA
Jerry Nolen, Argonne National Laboratory

Jianjun Yang, MIT/PSI
Jose Alonso, MIT
Joseph Minervini, MIT
Larry Bartoszek, Bartoszek Engineering
Leandro Piazza, INFN-Catania
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Roger Barlow, University of Huddersfield
Santo Gammino, INFN-Catania
Sebastiano Albergo, CSFSM-Sicily, Italy
Tim Koeth, University of Maryland
Todd Mawhinney, Best, Inc.
Willem Kleeven, IBA-Research

Five Years of Running at KamLAND

Inverse β Decay (IBD)



Accelerator	60 MeV/amu of H_2^+
Current	10 mA of protons on target
Power	600 kW
Duty cycle	90%
Run period	5 years (4.5 years live time)
Target	^9Be surrounded by ^7Li (99.99%)
$\bar{\nu}$ source	^8Li β decay ($\langle E_\nu \rangle = 6.4$ MeV)
$\bar{\nu}_e/1000$ protons	14.6
$\bar{\nu}_e$ flux	$1.29 \times 10^{23} \bar{\nu}_e$
Detector	KamLAND
Fiducial mass	897 tons
Target face to detector center	16 m
Detection efficiency	92%
Vertex resolution	$12 \text{ cm}/\sqrt{E} \text{ (MeV)}$
Energy resolution	$6.4\%/\sqrt{E} \text{ (MeV)}$
Prompt energy threshold	3 MeV
IBD event total	8.2×10^5
$\bar{\nu}_e$ -electron event total	7200

820,000 IBD events

➤ **Sterile neutrino search**

7,200 $\bar{\nu}_e$ -electron events

➤ Measure $\sin^2\theta_w$ to 3.2%

➤ Probe weak couplings and nonstandard interactions (NSIs)



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Accelerator Science

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SYNOPSIS

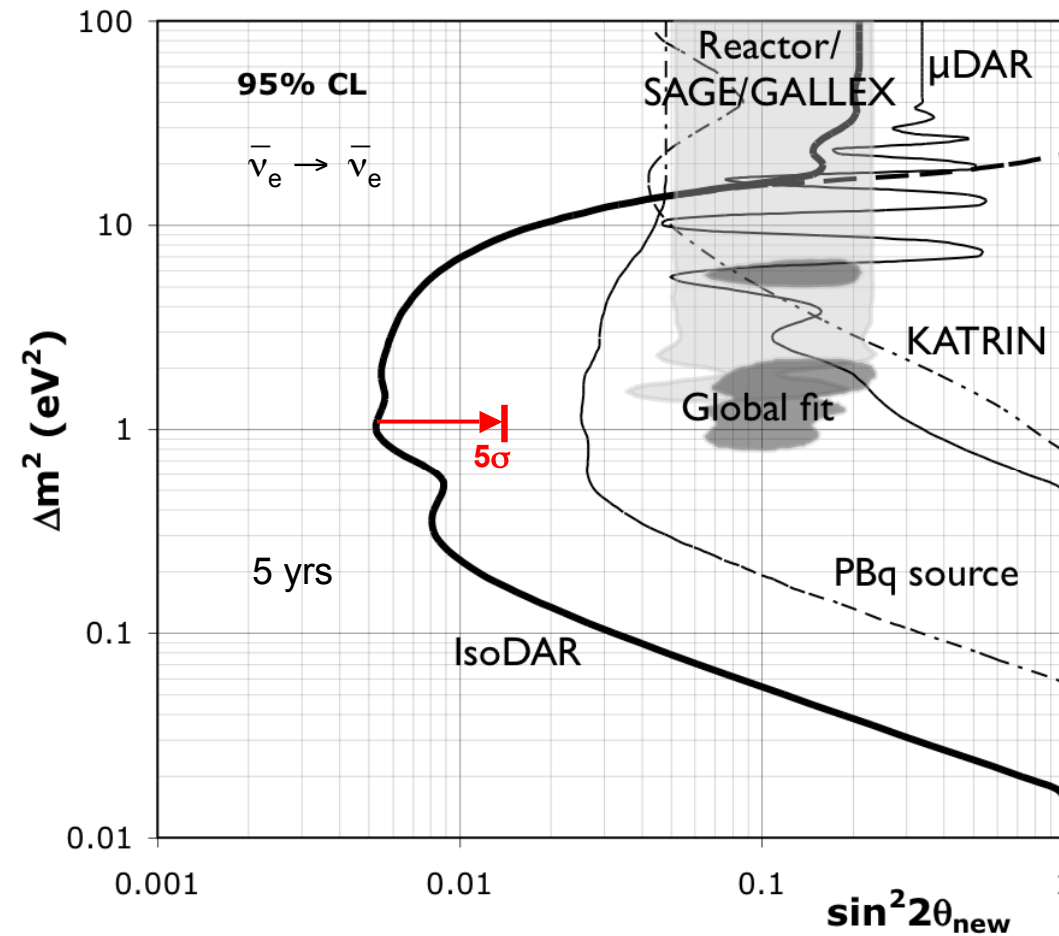
Particle accelerator systems have been key drivers for a broad array of fundamental discoveries and transformational scientific advances since the early 20th century. Since their inception, they have also been core components of U.S. technological innovation and economic competitiveness.

The Accelerator Science program will support and foster research at universities that exploits the educational and discovery potential of basic accelerator physics research, and allows the development of transformational discoveries in this crosscutting academic discipline. In particular, this program seeks to support research with the potential to disrupt existing paradigms and advance accelerator science at a fundamental level, such as enabling discoveries that lead to novel, compact, powerful, and/or cost-effective accelerators. Key questions that this program will address include: what are the fundamental limitations affecting the acceleration, control, intensity, and quality of particle beams? What novel approaches can be employed to substantially increase accelerating gradients? How can developments in other fields lead to new approaches in accelerator science and beam physics?

The goal of this program is to seed and support fundamental accelerator science at universities as an academic discipline, providing the foundation in knowledge and workforce upon which major advances in accelerator-driven technologies will be based. An important component of the program will be the support and training of the next generation of accelerator scientists, including students, postdoctoral researchers, and junior faculty, who will lead innovations in the field and will form the backbone of the

IsoDAR $\bar{\nu}_e$ Disappearance Oscillation Sensitivity (3+1)

820,000 IBD events in 5 years of running



➤ Global fit can be ruled out at $> 5\sigma$ in 4 months of running!